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ABSTRACT

Teaching procedures of Project Physics Unit 6 are presented to help teachers make effective use of learning materials. Unit contents are discussed in connection with teaching aid lists, multi-media schedules, schedule blocks, and resource charts. Brief summaries are made for transparencies, 16mm films, and reader articles. Included is information about the background and development of each unit chapter, procedures in demonstrations, apparatus operations, notes on the student handbook, and an explanation of film loops. Additional articles are concerned with objects dated by radiocarbon, radiation safety, properties of radiations, radioactive sources, radioactivity determination by electroscopes, and radiation detecting devices. Scalers, counters, Geiger tubes, and cadmium selenide photocells are analyzed; and a bibliography of references is given. Solutions to the study guide are provided in detail, and answers to test items are suggested. The sixth unit of the text, with marginal comments on each section, is also compiled in the manual. The work of Harvard Project Physics has been financially supported by: the Carnegie Corporation of New York, the Ford Foundation, the National Science Foundation, the Alfred P. Sloan Foundation, the United States Office of Education, and Harvard University. (CC)

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Project Physics **Teacher Guide** 6

An Introduction to Physics

The Nucleus

SE015 548

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Project Physics **Text**

An Introduction to Physics **6** The Nucleus

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Welcome to the study of physics. This volume, more of a student's guide than a text of the usual kind, is part of a whole group of materials that includes a student handbook, laboratory equipment, films, programmed instruction, readers, transparencies, and so forth. Harvard Project Physics has designed the materials to work together. They have all been tested in classes that supplied results to the Project for use in revisions of earlier versions.

The Project Physics course is the work of about 200 scientists, scholars, and teachers from all parts of the country, responding to a call by the National Science Foundation in 1963 to prepare a new introductory physics course for nationwide use. Harvard Project Physics was established in 1964, on the basis of a two-year feasibility study supported by the Carnegie Corporation. On the previous pages are the names of our colleagues who helped during the last six years in what became an extensive national curriculum development program. Some of them worked on a full-time basis for several years; others were part-time or occasional consultants, contributing to some aspect of the whole course; but all were valued and dedicated collaborators who richly earned the gratitude of everyone who cares about science and the improvement of science teaching.

Harvard Project Physics has received financial support from the Carnegie Corporation of New York, the Ford Foundation, the National Science Foundation, the Alfred P. Sloan Foundation, the United States Office of Education and Harvard University. In addition, the Project has had the essential support of several hundred participating schools throughout the United States and Canada, who used and tested the course as it went through several successive annual revisions.

The last and largest cycle of testing of all materials is now completed; the final version of the Project Physics course will be published in 1970 by Holt, Rinehart and Winston, Inc., and will incorporate the final revisions and improvements as necessary. To this end we invite our students and instructors to write to us if in practice they too discern ways of improving the course materials.

The Directors
Harvard Project Physics

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Prologue In Unit 6 we shall dig deeper into the problem of the constitution of matter by studying the atomic nucleus. In Unit 5 we learned that the atom consists of a very small, positively charged nucleus surrounded by electrons. Experiments on the scattering of α particles showed that the nucleus has dimensions of the order of 10^{-14} m. Since the diameter of an atom is of the order of 10^{-10}m, the nucleus takes up only a minute fraction of the volume of an atom. The nucleus, however, contains nearly all of the mass of the atom, as is also shown by the scattering experiments. The existence of the atomic nucleus and its properties raised new questions. Is the nucleus itself made up of still smaller units? If so, what are these units and how are they arranged in the nucleus? What methods can be used to get answers to these questions? What experimental evidence do we have to guide us?

We saw in Unit 5 that the study of the properties and structure of atoms needed new physical methods. The methods that could be used to study the properties of bodies of ordinary size, that is, with dimensions of the order of centimeters or meters, could not yield information about the structure of atoms. It is reasonable to expect that it is still more difficult to get information telling us what, if anything, goes on inside the nucleus, which is such a small part of the atom. New kinds of experimental methods are needed and new kinds of experimental data must be obtained. New theories must be devised to help us correlate and understand the data. In these respects the study of the nucleus is still another step on the long road from the very large to the very small along which we have traveled in this course.

One of the first and most important steps on the road to understanding the atomic nucleus was the discovery of radioactivity in 1896. Our discussion of nuclear physics will, therefore, start with radioactivity. We shall see how the study of radioactivity led to additional discoveries, to the development of methods for getting at the nucleus, and to ideas about the constitution of the nucleus. In fact, the discovery that the atom has a nucleus was a consequence of the study of radioactivity. We shall examine the interaction between experiment and theory and the step-by-step development of ideas about the nucleus. We shall try to see how particular experimental results led to new ideas and how the latter, in turn, led to new experiments. This historical study is especially useful and interesting because nuclear physics is a new branch of physics, which has been developed over a relatively short period of time. The reports and papers in which discoveries have been made known are readily available. The

The energy released by nuclear reactions within stars makes them visible to us over vast distances. The star clouds shown here are over 10,000 light years away. The sun, a typical star, converts over 4 billion kg of hydrogen into radiant energy each second.

research is still going on, and at an ever-increasing rate. Progress in nuclear physics is closely related to modern technology, which both supplies tools for further research and applies some of the results of the research in practical ways. Some of these practical applications have serious economic and political effects, and we read about them almost daily in our newspapers.

When the use and control of nuclear technology is exciting front-page news, it may be hard to realize that the study of the atomic nucleus is connected with a chance discovery made in 1896. But it was that discovery which touched off the whole enterprise that we call nuclear physics, and it is there that we shall start.

Before 1939 the main industrial use of uranium and its compounds was in the manufacture of colored glass, and only small amounts of uranium were needed. The study of the radioactivity of uranium also required only small amounts of uranium ore. As a result, uranium was usually obtained as a not-especially desirable by-product of industrial processes. Since 1939, uranium has become extremely important for reasons we shall discuss in Chapter 24.

Uranium-prospecting can be done using airborne instruments. This method is faster than ground-based prospecting and can be used in many otherwise inaccessible places.

Uranium-ore is mined in both "hard-rock" operations, such as the one in Colorado shown at the left, and in open-pit operations such as the one in New Mexico shown below.

Chapter 21 Radioactivity

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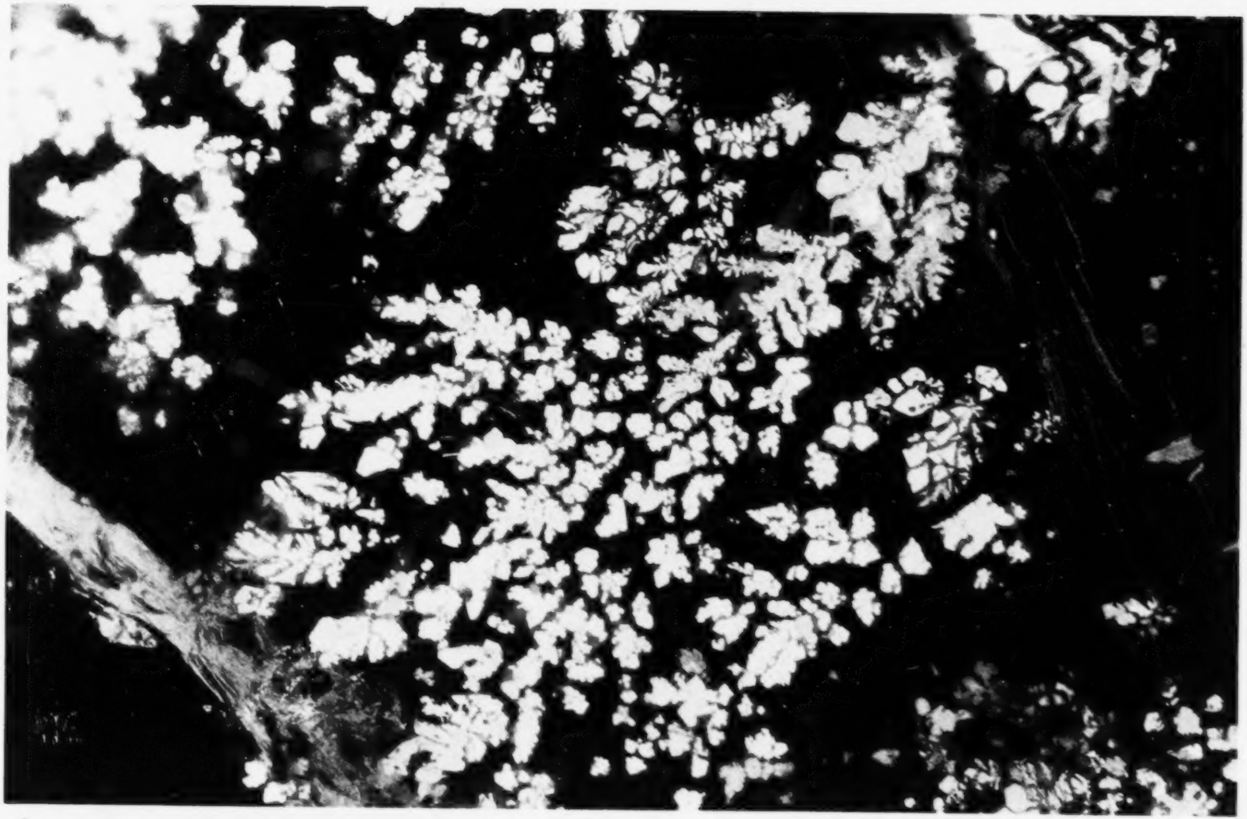


21.1 Becquerel's discovery. The discovery of the phenomenon known as "radioactivity" early in 1896 by the French physicist Henri Becquerel (1852-1908) was another of those "accidents" that illustrate how the trained and prepared mind is able to respond to an unexpected observation. Only two months before, in November 1895, Röntgen had discovered x rays. In doing so, he had set the stage for the discovery of radioactivity. Röntgen had pointed out that x rays came from the spot on the glass tube where the beam of cathode rays (high-speed electrons) was hitting, and that at the same time light was emitted from that spot. When the cathode ray beam was turned off, the spot of light on the face of the glass tube disappeared and the x rays coming from that spot stopped.

Summary 21.1
1. Very shortly after the discovery of x rays by Röntgen in 1895, Bequerel discovered "radioactivity."

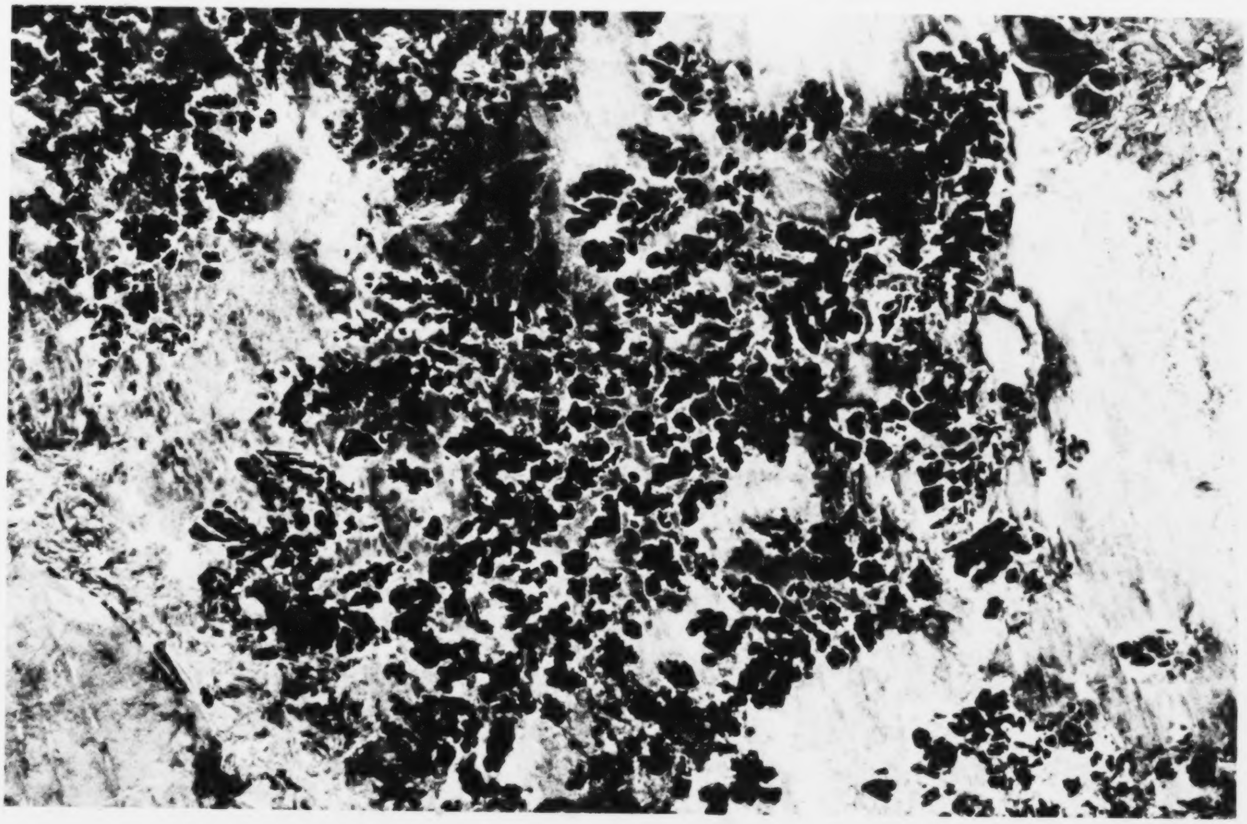
2. The new rays came from uranium; this led to two questions: a) what is the source of energy of these rays; and b) do other elements emit similar rays?

The emission of light by the glass tube when it is excited by the electron beam is an example of the phenomenon called fluorescence. A considerable amount of research was done on fluorescence during the latter part of the nineteenth

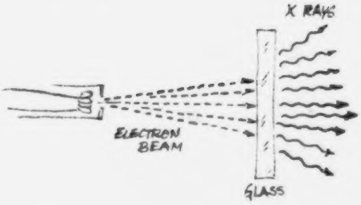
F 47: Discovery of radioactivity

Below is a photograph of the polished surface of a uranium-bearing rock. On the opposite page is an autoradiograph of the same surface made by placing the rock directly on a piece of film, packaging both in a light-tight container, and allowing the film to be exposed for about fifty hours.

D59: Mineral autoradiograph



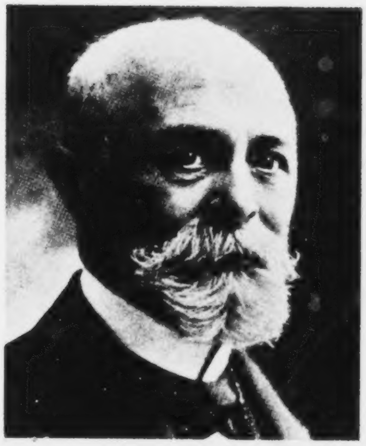
century. A substance is said to be fluorescent if it immediately emits visible light when struck by visible light of shorter wavelength, or by invisible radiations such as ultraviolet light, or by a beam of electrons. Fluorescence stops immediately when the exciting light is turned off. (The term phosphorescence is generally applied to an emission of visible light which continues after the exciting light is turned off.)



X-ray production by bombardment of electrons on glass.

Since the x rays also came from the spot which showed fluorescence it seemed logical to see if there was a closer connection than Röntgen had suspected between x rays and fluorescence or phosphorescence. Becquerel was doubly fortunate in having the necessary materials and training to study this problem. He was the son and grandson of physicists who had made important contributions in the field of phosphorescence. In his Paris laboratory he had devised an instrument for examining materials in complete darkness a small fraction of a second after they had been exposed to a brilliant light. The question occurred to Becquerel: do minerals or other bodies that are made to fluoresce (or phosphoresce) with sufficient intensity also emit x rays in addition to the light rays? He tested a number of substances by exposing them to sunlight and looking to see whether they emitted x rays while phosphorescing. One of them was a salt of the metal uranium, a sample of potassium-uranyl sulfate. In his words:

> I wrapped a...photographic plate...with two sheets of thick black paper, so thick that the plate did not become clouded by exposure to the sun for a whole day. I placed on the paper a [crust] of the phosphorescent substance, and exposed the whole thing to the sun for several hours. When I developed the photographic plate I saw the silhouette of the phosphorescent substance in black on the negative. If I placed between the phosphorescent substance and the paper a coin or a metallic screen pierced with an open-work design, the image of these objects appeared on the negative. The same experiment can be tried with a thin sheet of glass placed between the phosphorescent substance and the paper, which excludes the possibility of a chemical action resulting from vapors which might emanate from the substance when heated by the sun's rays.
>
> We may therefore conclude from these experiments that the phosphorescent substance in question emits radiations which penetrate paper that is opaque to light....



Henri Becquerel (1852-1908) received the 1903 Nobel Prize in physics (for the discovery of natural radioactivity) along with Pierre and Marie Curie (for the discovery of the radioactive elements radium and polonium).

Becquerel was careful to conclude from this experiment only that "penetrating radiations" were emitted from the phosphorescent substance. He did not conclude that the substance emitted x rays while it phosphoresced because he had not yet verified that the radiations were x rays (though the radiations were transmitted through the black paper), or that they were actually related to the phosphorescence (though he strongly suspected that they were). Before he could investigate these possibilities, he made this discovery:

> ...among the preceding experiments some had been made ready on Wednesday the 26th and Thursday the 27th of February [1896]; and as on those days the sun only showed itself intermittently, I kept my arrangements all prepared and put back the holders in the dark in the drawer of the case, and left in place the crusts of uranium salt. Since the sun did not show itself again for several days, I developed the photographic plates on the 1st of March, expecting to find the images very feeble. The silhouettes appeared on the contrary with great intensity. I at once thought that the action might be able to go on in the dark....

This unexpected result may appear to students to be only a result of a lucky break, but it should be pointed out that the discovery was made possible by Bequerel's research methods, which exemplify science at its best.

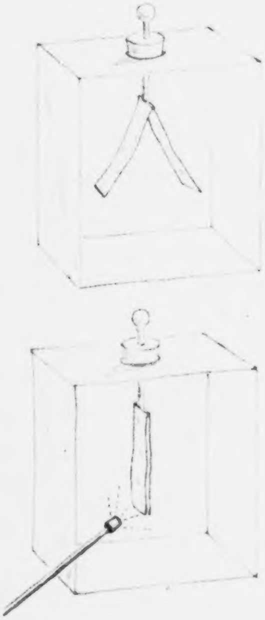
Also he had the knowledge and good sense to recognize the significance of his accidental finding. For contrast, refer students to the marginal note on page 54 in Text 5.

Further experiments verified this thought: whether or not the uranium compound was being excited by sunlight to phosphoresce, it continuously emitted something that could penetrate lightproof paper and other substances opaque to light, such as thin plates of aluminum or copper. Becquerel found that all the compounds of uranium—many of which were not phosphorescent at all—as well as metallic uranium itself had the same property. The amount of action on the photographic plate did not depend on the particular compound of uranium used, but only on the amount of uranium present.

Becquerel also found that the radiations from a sample of uranium were persistent and did not change, either in intensity or character, with the passing of time. No change in the activity was observed when the sample of uranium or of one of its compounds was exposed to ultraviolet light, infrared light or x rays. The intensity of the uranium radiation or "Becquerel rays," as they came to be known, was the same at room temperature (20°C), at 200°C and at the temperature at which oxygen and nitrogen (air) liquefy, about -190°C.

Becquerel also showed that the radiations from uranium produced ionization in the surrounding air. They could discharge positively or negatively charged bodies such as electroscopes. Thus, the uranium rays resemble x rays in two important respects: their penetrating power and their ionizing power. Both kinds of rays were invisible to the unaided eye, although they affected photographic plates. But x rays and Becquerel rays differed in at least two important ways: compared to x rays, these newly discovered rays from uranium were less intense, and they could not be turned off. Becquerel showed that even after a period of three years a given piece of uranium and its compounds continued to emit radiations spontaneously.

The air around the charged leaves of the electroscope becomes ionized by radiation from the uranium. The charged particles produced can drift to the leaves and neutralize their charge. The time taken for the leaves to fall is a measure of the rate of ionization of the gas, and hence of the intensity of the α-particle activity.



The years 1896 and 1897 were years of high excitement in physics, to a large extent because of the great interest in x rays and in cathode rays. Since, as quickly became evident, x rays could be used in medicine, they were the subject of much research. But the properties of the Becquerel rays were less spectacular and little work was done on them in the period from the end of May 1896 until the end of 1897. Even Becquerel himself turned his attention to other work. But the fact that the invisible rays from uranium and its compounds could not be turned off began to attract attention.

Two questions were asked: first, what was the source of the energy creating the uranium rays and making it possible for them to penetrate opaque substances? And second, did any other of the seventy or more elements (that were known in 1898) have properties similar to those of uranium? The first question was not answered for some time although it was considered seriously. The second question was answered within a short time by the Curies, who thereby, early in 1898, opened a whole new chapter in physical science.

Q1 Why was Becquerel experimenting with a uranium compound?

Q2 How did uranium compounds have to be treated in order to emit the "Becquerel rays"?

Q3 What was the puzzling property of the "Becquerel rays"?

Summary 21.2
1. Thorium also was found to be radioactive.

2. The quantitative investigation of Marie and Pierre Curie led to the conclusion that radioactivity is a property of the atoms of elements rather than the chemical combinations or physical conditions of the elements.

SG 21.1

3. Two new elements were discovered, both radioactive: polonium and radium.

21.2 Other radioactive elements are discovered. One of Becquerel's colleagues in Paris was the physicist Pierre Curie, who had recently married a Polish-born physicist, Marie Sklodowska. Marie Curie undertook a systematic study of the Becquerel rays and looked for other elements and minerals that might emit them. Using a sensitive electrometer which her husband had recently invented, she measured the small electric current produced when the rays ionized the air through which they passed. This current was assumed to be (and is) proportional to the intensity of the rays. With this new technique, she could find numerical values for the effect of the rays, and these values were reproducible within a few percent from one experiment to the next.

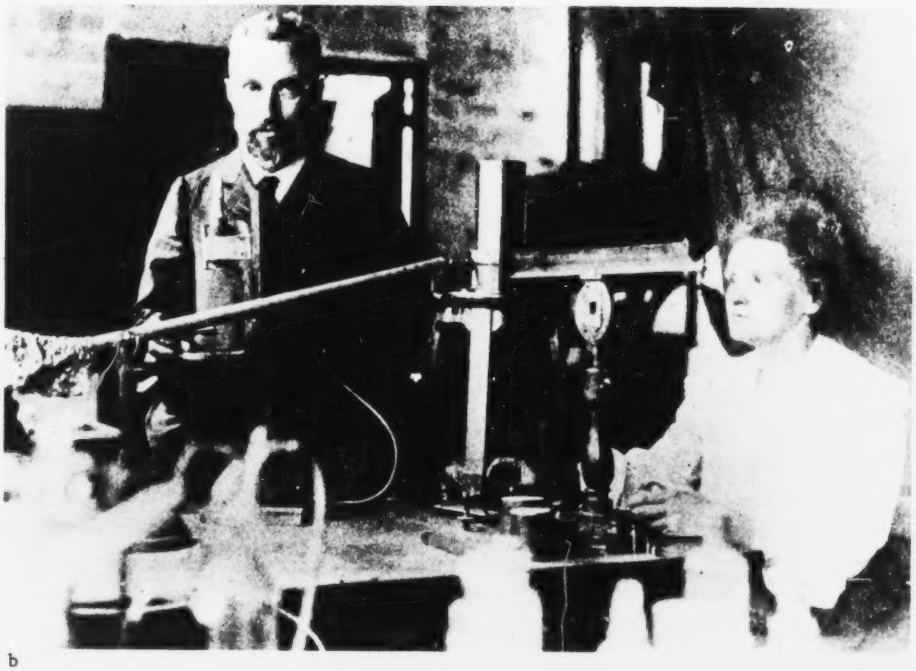
One of her first results was the discovery that the element thorium (Th) and its compounds emitted radiations with properties similar to those of the uranium rays. (The same finding was made independently in Germany by G. C. Schmidt, at about the same time.) The fact that thorium emits rays like those of uranium was of great importance because it showed that uranium was not the only source of the mysterious rays. The discovery spurred the search for still other elements which might emit similar rays. The fact that uranium and thorium were the elements with the greatest known atomic masses indicated that the very heavy elements might have special properties different from those of the lighter elements.

The evident importance of the problems raised by the discovery of the uranium and thorium rays led Pierre Curie to lay aside his researches in other fields of physics and work with his wife on these new problems. They found that the intensity of the emission from any thorium compound was directly proportional to the fraction by weight of the metallic element thorium present. (Becquerel found a similar result for uranium compounds.) Moreover, the amount of radiation was independent of the physical conditions or the chemical combination of the active elements. These results led the Curies to the conclusion that the emission of the rays depended only on the presence of atoms of either of the two elements uranium or thorium. The rate of emission was not affected either by changes of the physical state or by chemical changes of the compounds containing atoms of the elements. To the Curies, these results meant that an explanation of radioactivity lay within the atom itself and not in its chemical combinations. The Curies also deduced that chemical compounds or mixtures containing uranium or thorium are more or less active depending on whether they contain a greater or smaller proportion of these metals. Atoms of other elements that were present were simply inactive or absorbed some of the radiation.

These ideas were especially important because they helped the Curies interpret their later experiments. For example, in their studies of the activity of minerals and ores of uranium and thorium they examined the mineral pitchblende, an ore containing about 80 percent uranium oxide (U_3O_8). They found that the emission from pitchblende, as measured by its effect in ionizing air, was about four or five times as great as that to be expected from the amount of uranium in the ore. The other elements known at the time to be associated with uranium in pitchblende, such as bismuth and barium, had been shown to be inactive. If emission of rays is an atomic phenomenon, the unexpected pitchblende activity could be explained only by the presence in pitchblende of another element more active than uranium itself.

To explore this hypothesis, the Curies applied chemical separation processes to a sample of pitchblende in order to try to isolate this hypothetical active substance. After each separation process, the products were tested, the inactive part discarded and the active part analyzed further.

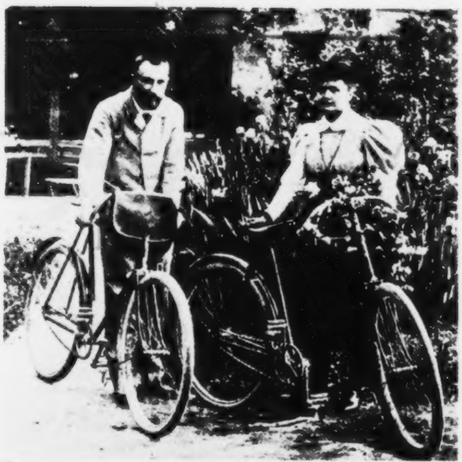
a



b

a. e. Marie Curie.
b. c. Marie and Pierre.
d. Marie, Irene and Pierre; all 3 won Nobel prizes!

Pierre Curie (1859-1906) studied at the Sorbonne in Paris. In 1878 he became an assistant teacher in the physical laboratory there, and some years later, professor of physics. He was well known for his research on crystals and magnetism. He married Marie Sklodowska in 1895 (she was 28 years old). After their marriage, Marie undertook her doctoral research on radioactivity. In 1898 Pierre joined his wife in this work. Their collaboration was so successful that in 1903 they were awarded the Nobel Prize in physics, which they shared with Becquerel. Pierre Curie was run over and killed by a horsedrawn vehicle in 1906. Marie Curie was appointed to his professorship at the Sorbonne, the first woman to have this post. In 1911 she was awarded the Nobel Prize in chemistry for the discovery of the two new elements, radium and polonium. She is the only person who has won two Nobel science prizes. The rest of her career was spent in the supervision of the Paris Institute of Radium, a center for research on radioactivity and the use of radium in the treatment of cancer. Marie Curie died in 1934 of leukemia, a form of cancer of the leukocyte-forming cells of the body, probably caused by over-exposure to the radiations from radioactive substances.



c

d

e

Finally, the Curies obtained a highly active product which presumably consisted mainly of the unknown element. In a note called "On a New Radioactive Substance Contained in Pitchblende" and submitted to the French Academy of Sciences in July of 1898, they reported:

In this note the term "radioactivity" was used for the first time.

> By carrying on these different operations...finally we obtained a substance whose activity is about 400 times greater than that of uranium....
>
> We believe, therefore, that the substance which we removed from pitchblende contains a metal which has not yet been known, similar to bismuth in its chemical properties. If the existence of this new metal is confirmed, we propose to call it polonium, after the name of the native country of one of us.

Six months after the discovery of polonium (given the symbol Po), the Curies separated another substance from pitchblende and found the emission from it so intense as to indicate the presence of still another new element even more radioactive than polonium. This substance had an activity per unit mass 900 times that of uranium and was chemically entirely different from uranium, thorium or polonium. Spectroscopic analysis of this fraction revealed spectral lines characteristic of the inactive element barium, but also a line in the ultraviolet region that did not seem to belong to any known element. The Curies reported their belief that the substance, "although for the most part consisting of barium, contains in addition a new element which produced radioactivity and, furthermore, is very near barium in its chemical properties." For this new element, so extraordinarily radioactive, they proposed the name radium (chemical symbol Ra).

A next step in making the evidence for the newly discovered elements more convincing was to determine their properties, especially the atomic masses. The Curies had made it clear that they had not yet been able to isolate either polonium or radium in pure form, or even to obtain a pure sample of a compound of either element. From the material containing the strongly radioactive substance that they called radium, they had separated a part consisting of barium chloride mixed with a presumably very small quantity of radium chloride. Additional separations gave an increasing proportion of radium chloride. The difficulty of this task is indicated by the Curies' remark that radium "is very near barium in its chemical properties," for it is very difficult to separate elements whose chemical properties are similar. Moreover, to obtain their highly radioactive substances in usable amounts, they had to start with a very large amount of pitchblende.

With an initial 100-kg shipment of pitchblende (from which the uranium salt had been removed to be used in the manufacture of glass) the Curies went to work in an abandoned woodshed at the School of Physics where Pierre Curie taught. Failing to obtain financial support, the Curies made their preparations without technical help in this "laboratory." Marie Curie wrote later:

> I came to treat as many as twenty kilograms of matter at a time, which had the effect of filling the shed with great jars full of precipitates and liquids. It was killing work to carry the receivers, to pour off the liquids and to stir, for hours at a stretch, the boiling material in a smelting basin.

From the mixture of radium chloride and barium chloride only the average atomic mass of the barium and radium could be computed. At first an average value of 146 was obtained, as compared with 137 for the atomic mass of barium. After many additional purifications which increased the proportion of radium chloride, the average atomic mass rose to 174. Continuing the tedious purification process for four years, during which she treated several tons of pitchblende residue, Marie Curie was able to report in July 1902 that 0.1 g of radium chloride had been obtained, so pure that spectroscopic examination showed no evidence of any remaining barium. She determined the atomic mass of radium and obtained the value 225 (the present-day value is 226.03). In 1910, Marie Curie isolated radium metal by means of electrolysis of molten radium chloride. The activity of pure radium is more than a million times that of the same mass of uranium; the present yield of radium from one ton of high-grade uranium ore is about 0.2 g.

Q4 How is radioactive emission of an element affected by being combined into different compounds?

Q5 Why did the Curies suspect the existence of another radioactive material in uranium ore?

Q6 What was the main difficulty in producing pure radium?

21.3 The penetrating power of the radiation: α, β and γ rays. The extraordinary properties of radium excited interest both inside and outside the scientific world. The number of workers in the field of radioactivity increased rapidly as the importance of the subject and the chance that it seemed to offer of further discoveries came to be recognized. The main question that attracted attention was: what is the nature of the mysterious radiations emitted by radioactive bodies, radiations which can affect photographic plates and ionize air even after passing through solid metal sheets?

Summary 21.3

1. Rutherford studied the nature of the radioactive rays by measuring their absorption in thin foils. He found the rays to be of two types, which he called α and β.

2. A third type, γ rays, were discovered by Villard.

3. α's, which cause the most ionization when passing through matter, have the shortest range. γ's have the greatest range.

21.3

In 1899, Ernest Rutherford, whose theory of the nuclear atom has been discussed in Chapter 19, started to seek answers to this question. He studied the absorption of the radiation from uranium by letting the radiation pass through different thicknesses of aluminum foils. Rutherford thought that the way in which the intensity of the radiation varied with the thickness of the aluminum might indicate whether the rays were of more than one kind. He found that, after the passage of the radiation through 0.002 cm of aluminum, the intensity of the radiation (as measured by the ionization produced in air) was reduced to about one-twentieth of the initial value. The addition of a thickness of 0.001 cm of aluminum had only a very small further effect in cutting down the intensity. The intensity could be reduced further by about one half, by passing the radiation through about fifty times as much foil. Rutherford concluded from these experiments that uranium emits at least two distinct kinds of rays—one that is very readily absorbed, which he called for convenience α rays (alpha rays), and the other more penetrating, which he called β rays (beta rays).

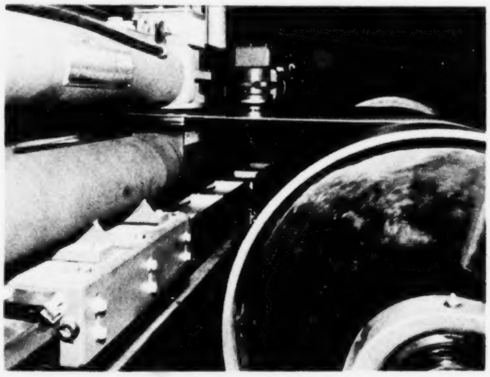
See "Rutherford" in Project Physics Reader 6.

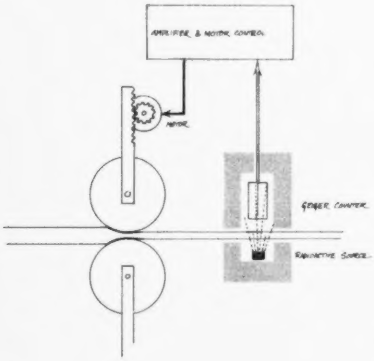
In 1900 the French physicist P. Villard observed that the emission from radium contained rays much more penetrating than even the β rays, this type of emission was given the name γ (gamma) rays. The penetrating power of the three types of rays, as known at the time, is compared in the table below, first published by Rutherford in 1903:

Radiation Type	Approximate thickness of aluminum traversed before the radiation intensity is reduced to one-half its initial value
α rays	0.0005 cm
β rays	0.05 cm
γ rays	8 cm

E45*: Range of alpha and beta particles.

The absorption of β rays gives rise to many modern practical applications of radioactivity. One example is the thickness gauge illustrated in the photograph and drawing at the right. Sheet metal or plastic is reduced in thickness by rolling. The thickness is measured continuously and accurately by determining the intensity of the β rays that pass through the sheet. The rolling is continued until the desired sheet thickness is obtained.





Of the three kinds of rays, the α rays are the most strongly ionizing and the γ rays the least; the penetration is inversely proportional to the ionization. The penetrating power of the α rays is low because they expend their energy very rapidly in causing intense ionization. Alpha rays can be stopped, that is, completely absorbed, by about 0.006 cm of aluminum, by a sheet of ordinary writing paper or by a few centimeters of air. Beta rays can travel many meters in air, but can be stopped by aluminum less than a centimeter thick. Gamma rays can pass through many centimeters of lead, or through several feet of concrete, before being almost completely absorbed. One consequence of these properties of the rays is that heavy and expensive shielding is sometimes needed in the study or use of radiations, especially γ rays, to protect people from harmful effects of the rays. In some cases these "radiation shields" are as much as 10 feet thick. One example of shielding around a target at the output of an electron accelerator is shown below.

SG 21.2

Q7 List α, β and γ rays in order of the penetrating ability.

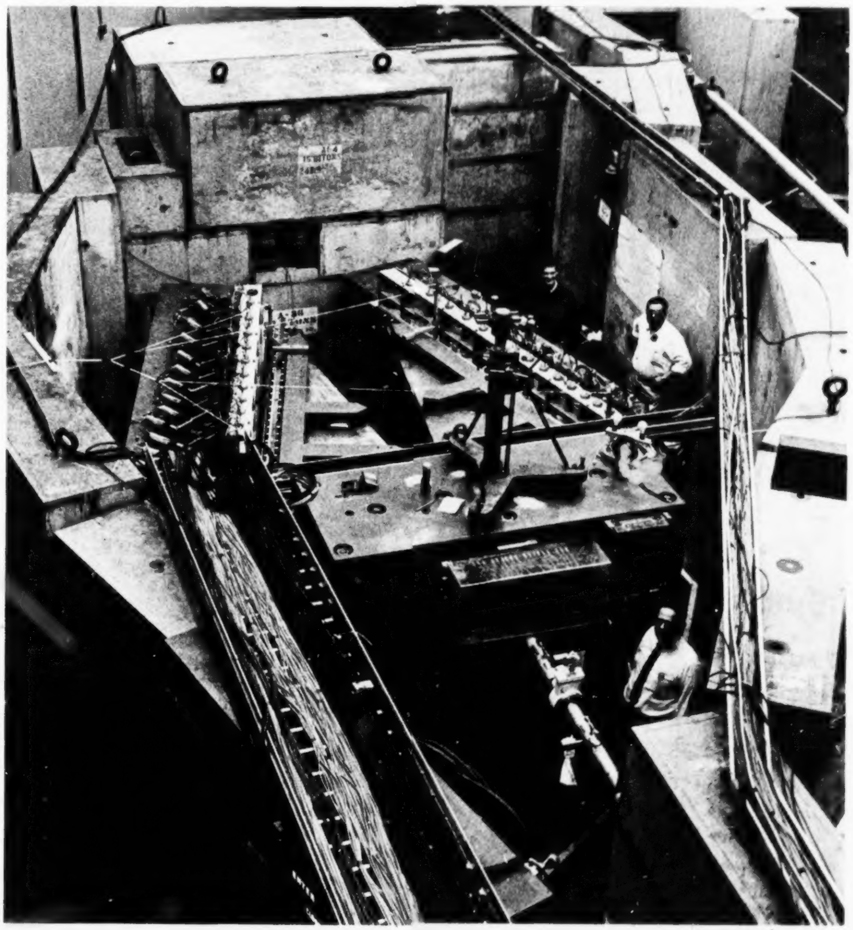
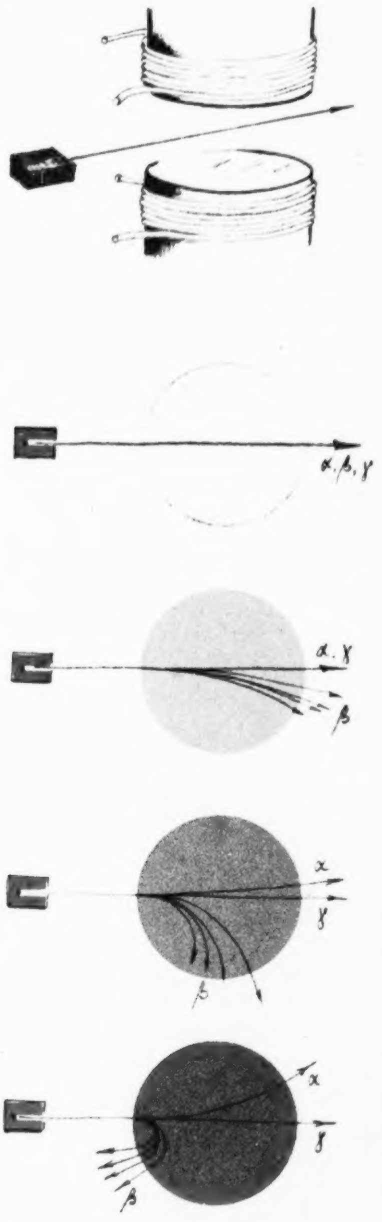


Fig. 21.1 Separation of the α, β and γ rays from a radioactive material by their passage through a magnetic field. (Unless the apparatus were in a vacuum, the path of the α particles would be much shorter than indicated.)



21.4 The charge and mass of α, β and γ rays. Another method used to study the rays was to direct them through a magnetic field to see if they were deflected or deviated from their initial directions by the action of the field. This method, which provides one of the most widely used tools for the study of atomic and nuclear events, is based on the now familiar fact that a force acts on a charged particle moving across a magnetic field. As discussed in Unit 4, this force is always at right angles to the direction of motion of the charged particle. The particle experiences a continual deflection and, in a uniform field, moves along the arc of a circle.

This property had been used in the 1890's by J. J. Thomson in his studies of cathode rays. He showed that these rays consist of very small negatively charged particles, or electrons (Chapter 18). Becquerel, the Curies and others found that the α, β and γ rays behaved differently from one another in a magnetic field. The behavior of the rays is illustrated in the diagrams in the margin.

Suppose that some radioactive material, such as uranium, is placed at the end of a narrow hole in a lead block; a narrow beam consisting of α, β and γ rays escapes from the opening. If a strong, uniform magnetic field is applied perpendicular to the plane of the page away from the reader, the three types of rays are separated from each other. The γ rays continue in a straight line without any deviation. The β rays are deflected strongly downwards, moving in circular arcs of differing radii. The α rays are bent slightly upwards in a circular arc of large radius, but are rapidly absorbed in the air after moving only a few centimeters from the lead block.

The direction of the deflection of the β rays was the same as that observed earlier in Thomson's studies of the properties of cathode rays. It was concluded, therefore, that the β rays, like cathode rays, consist of negatively charged particles. Since the direction of the deflection of the α rays was opposite to that of the β rays, it was concluded that the α rays consist of positively charged particles. Since the γ rays were not deflected, it was concluded that they were neutral, that is, had no electric charge; no conclusion could be drawn from this type of experiment as to whether the γ rays are, or are not, particles. The magnitude of the deflections suggests that the α particles have a much larger momentum than the β particles. The conclusions concerning the signs of the electric charges carried by the rays were tested by directing the deflected beam into an electroscope and determining the

T40: Separation of α, β, γ rays

charge that builds up on the leaves. This was done by the Curies in 1900 to confirm the negative charge of the β particles.

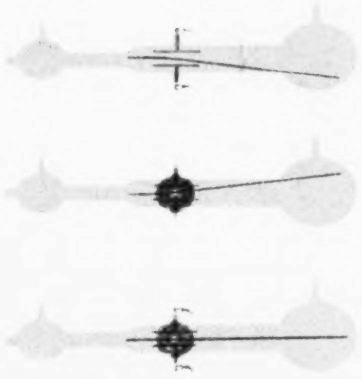


Fig. 21.2 If an electric field and a magnetic field are at right angles, each will deflect charged particles. There will be only one speed for which there will be no deflection.

The q/m for the beta particles could be found from their deflection in magnetic and electric fields. Becquerel, investigating β particles in 1900, used a procedure which was essentially the same as that used by J. J. Thomson in 1897 to obtain a reliable value for the ratio of charge q_e to mass m_e for the particles in cathode rays (thereby establishing quantitatively the existence of the electron). By sending β rays through crossed electric and magnetic field, he was able to calculate the speed of the β particles. He obtained a value of q/m for β particles which was in close enough agreement with that found by J. J. Thomson for the electron to permit the deduction that the β particles are electrons.

The nature of the α radiation was more difficult to establish. The value of q/m for α particles (4.8×10^7 coul/kg) was about 4000 times smaller than q/m for β particles. It was therefore necessary to use a very strong magnetic field to produce measurable deflections. Other evidence available at the time indicated that q for an α particle was not likely to be smaller than for a β particle. It was therefore concluded that m would have to be much larger for the α particle than for the β particle.

Summary Sec 21.4
Properties of the radioactive rays were studied by passing them through magnetic fields. It was found that:
a) γ rays weren't charged;
b) β rays were electrons;
c) α rays might be helium nuclei.

SG 21.3
SG 21.4

In fact, the value of q/m given above for α particles is just one half that of q/m for a hydrogen ion. The value would be explained in a reasonable way if the α particle were like a hydrogen molecule minus one electron (H_2^+), or else if it were a helium atom (whose mass was known to be about four times that of a hydrogen atom) without its two electrons (He^{++}). Other possibilities might have been entertained—for example, bare nuclei of carbon, nitrogen or oxygen would have about the same q/m ratio. But there were other reasons for thinking that α particles were related to helium.

Q8 What was the evidence that β particles are electrons?

Q9 What observation led to the suggestion that α particles are much more massive than β particles?

21.5 The identity of α rays: Rutherford's "mousetrap." It was known that the gas helium was always found imprisoned in radioactive minerals. In addition, Sir William Ramsey and Frederick Soddy had discovered, in 1903, that

Summary 21.5
Rutherford showed that α-particles were helium nuclei; this implied that one nucleus can change in two other nuclei.

T4-1: Rutherford's α particle "mousetrap"

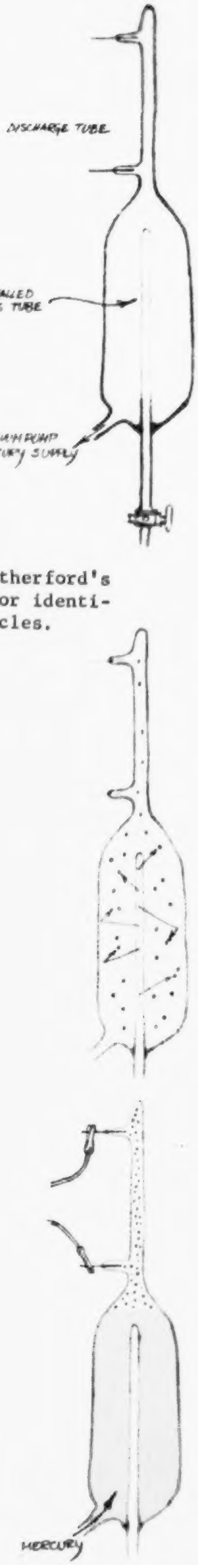


Fig. 21.3 Rutherford's "mousetrap" for identifying α particles.

helium was liberated by a radioactive compound, radium bromide. Rutherford made the hypothesis that the α particle is a doubly-ionized helium atom—a He atom minus two electrons —or, as we would now say, the nucleus of a helium atom. In a series of experiments from 1906 to 1909 he succeeded in proving the correctness of his hypothesis in several different ways. The last and most convincing of these experiments was made in 1909, with T. D. Royds, by constructing what Sir James Jeans later called "a sort of mousetrap for α particles."

The experiment was based on the use of the radioactive element radon (Rn), which has properties that made it especially suitable for the experiment. Radon was discovered by Pierre Curie and A. Debierne in 1901. They placed some radium in a glass vessel and pumped air out of the vessel until the air pressure was very low. They then found that the pressure in the vessel increased because a gaseous substance was given off from the radium. A small amount of the gas collected in this way was found to be a strong α particle emitter. The gas was shown to be a new element and was called "radium emanation" and later "radon." Ramsey and Soddy showed that when this radon is stored in a closed vessel, helium always appears in the vessel. Thus helium is given off not only by radium bromide but also by radon.

Rutherford and Royds put a small amount of radon in a fine glass tube with a wall only one hundredth of a millimeter thick. This wall was thin enough so that α particles could pass through it. The tube was sealed into a thick-walled glass tube which had a discharge tube at the top. Fig. 21.3 shows diagrams of the apparatus. The air was pumped out of the outer tube and the apparatus was allowed to stand for about a week. During this time, while α particles from the radon passed through the thin walls of the inner tube, a gas gradually collected in the previously evacuated space. Mercury was then used to compress the gas and confine it in the discharge tube. When a potential difference was applied to the electrodes of the discharge tube, an electric discharge was produced in the gas. The resulting light was examined with a spectroscope and the spectral lines characteristic of helium were seen. In a separate control experiment, helium gas itself was put in the inner, thin-walled tube instead of radon, and did not leak through the wall of the inner tube.

Now it was clear how to interpret the results of these experiments: Rutherford could safely conclude that the helium gas that collected in the outer tube was formed from α particles that had passed into the outer tube. Even at low gas pressures electrons were present so that the α particles could form neutral helium atoms by capturing electrons.

Rutherford's conclusion implied that an atom of an element (radon) spontaneously emits a fragment (an α particle) which consists of the nucleus of another element (helium). The result implied that a transmutation, the production of one element from another, occurs when radon emits an α particle.

See "The Nature of the Alpha Particle" in Project Physics Reader 6.

Q10 How did Rutherford know that the gas which appeared in the tube was helium?

21.6 Radioactive transformations. The emission of α and β particles presented difficult and important questions with respect to existing ideas of matter and its structure. The rapid development of chemistry in the nineteenth century had made the atomic-molecular theory of matter highly convincing. According to this theory, a pure element consists of identical atoms, and these atoms are indestructible and unchangeable. But, if a radioactive atom emits an α particle (shown to be an ionized helium atom), can the radioactive atom remain unchanged? The answer seems clearly to be "no"; a transmutation must take place in which the radioactive atom is changed to an atom of a different chemical element.

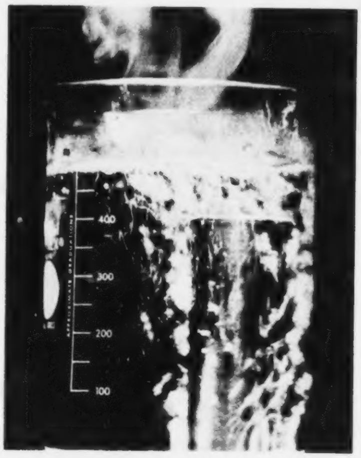
Summary 21.6
1. All radioactive atoms are subject to division; a large energy release results from the division.

2. Rutherford and Soddy postulated the theory of radioactive transformation.

3. Radium atoms undergo a series of transformations, ending in a stable "daughter" element.

If an atom emits an α particle, a substantial part of its mass will be carried away by the α particle. What about the atoms which emit β particles? The β particle is not as massive as the α particle but its mass is not zero, and a radioactive atom must undergo some change when it emits a β particle. It was difficult to escape the conclusion that all radioactive atoms are, in fact, subject to division (into two parts of markedly unequal mass), a conclusion contrary to the basic concept that the atom is indivisible.

Another fundamental question arose in connection with the energy carried by the rays emitted by radioactive substances. As early as 1903 Rutherford and Soddy, and Pierre Curie and a young co-worker, A. Laborde, noted that radium emitted a large amount of energy—so large that a sample of radium kept itself at a higher temperature than the surrounding air merely by absorbing some of the energy of the α particles emitted by atoms in the sample. Curie and Laborde found that one gram of radium releases about 100 calories of heat per hour (or 0.1 kilocalorie). Radium has the remarkable property that it can continue to release energy year after year, for hundreds and even thousands of years.



The water is being boiled by the heat produced by a small capsule of cobalt 60. This capsule, the first ever made to produce heat from radioactive cobalt, generated heat at the rate of 360 watts when this photo was taken.

The continuing release of such a quantity of heat could not be explained by treating radioactivity as if it were an ordinary chemical reaction. It was also clear that radioactivity did not involve chemical changes in the usual sense: energy was emitted by samples of pure elements; energy emission by compounds did not depend on the type of molecule in which the radioactive element was present. The origin of the production of heat had to be sought in some deeper changes within the atoms themselves.

Rutherford and Soddy proposed a bold theory of radioactive transformation to explain the nature of these changes. They proposed that when a radioactive atom emits an α or a β particle it really breaks into two parts—the α or β particle emitted, and a heavy left-over part, or residue, which is physically and chemically different from the "parent" atom. There was a good deal of evidence for the last part of the assumption. For example, there was the formation of radon from radium, discussed earlier. When the atomic mass of radon was determined, it turned out to be smaller than that of radium by just 4 atomic mass units, the mass of an α particle.

According to the proposal of Rutherford and Soddy, the formation of radon may be represented by means of a diagram:

$$\begin{tikzcd} & \alpha \\ Ra \arrow[ur] \arrow[rr] & & Rn \end{tikzcd}$$

In the diagram, Ra stands for an atom of radium and Rn for an atom of radon. An equation analogous to a chemical equation may be used equally well:

$$Ra \longrightarrow Rn + He \quad .$$

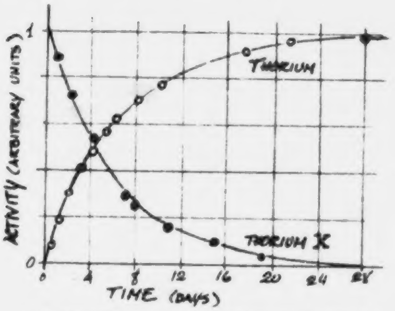
Here He stands for the helium atom formed when the α particle picks up two electrons and becomes neutral. The process may be described as the "disintegration" or "decay" or "transmutation" of radium into radon, with the emission of an α particle.

In addition to the example just cited, many decay processes had been found and studied, by the Curies, by Rutherford and his co-workers, and by others, and these processes fitted easily into the kind of scheme proposed by Rutherford and Soddy. Radon also is radioactive, emitting an α particle and thereby decaying into an atom of an element which was called "radium A" at the time. Radium A was shown to be polonium (Po).

$$Rn \longrightarrow Po + He \; .$$

Polonium is a solid, and also is radioactive. In fact, the original radium atoms undergo a series or chain of transformations into new, radioactive, "daughter" elements, ending

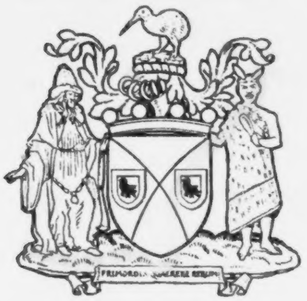
In 1900, the English physicist Sir William Crookes found that most of the observed activity of pure compounds of uranium was not due to that element, but to something else which could be separated chemically from the uranium. This active "something else" was called uranium X to distinguish it from uranium. Becquerel then separated the two substances and found that the activity of the uranium X decreased while that of the uranium increased. Rutherford and Soddy, of whom we shall hear more in Chapter 22, obtained similar results with compounds of thorium. Their results, published in 1903, are shown below.



Rutherford and Soddy received the Nobel prize in chemistry for their work on the radioactive transformation of one element into another.

In 1931 Rutherford was elevated to the British peerage becoming "Baron Rutherford of Nelson." It is said some similarity between parts of his coat of arms and the diagram above has been intentionally preserved.

RUTHERFORD OF NELSON.



with a "daughter" element which is stable, or non-radioactive. SG 21.5

Q11 Why couldn't radioactive decay be an ordinary chemical reaction?

Q12 What was it about the products of decay that indicated nuclei were being transmuted?

21.7 Radioactive decay series. The stable end-product of the decay of radium and its daughters was identified by its chemical behavior as lead. The chain beginning with radium has 10 members, some of which emit β particles rather than α particles. Gamma rays do not appear alone, but always together with an α particle or a β particle. Rutherford and Soddy also suggested that, since radium is always found in uranium ores, it may be a member of a series starting with uranium as the ancestor of all the members. Research showed that this is indeed the case. Each uranium atom may in time give rise to successive daughter atoms, radium being the sixth generation and stable lead the fifteenth.

Summary 21.7

1. Uranium atoms undergo a series of transformations, radium being the 6th generation and stable lead (Pb^{210}) the 15th.

2. Seperation of different members of the series is extremely difficult due to the close similarities in chemical properties and widely different decay rates.

Table 21.1 shows the members of the uranium-radium series. The significance of some of the symbols will be discussed in later sections. The number following the name of an element, as in uranium 238, indicates the atomic mass. Notice that there are heavier and lighter varieties of the element, for example, uranium 238 and 235, polonium 218, 214 and 210. Much more will be said about these varieties in the next chapter.

Two other naturally occurring radioactive series have been found; one starts with thorium 232 and the other with uranium 235 (see SG 22.7 and 22.8).

There is also a fourth series starting with artificially produced plutonium (see SG 22.9).

Table 21.1

Uranium-radium series

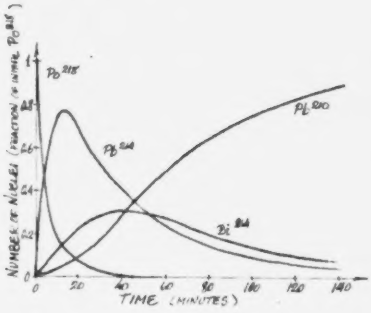
T42: Radioactive disintegration series

L6-1: Radioactive decay

Old name	Present name and symbol		Mode of decay	Half-life
Uranium I	Uranium 238	$_{92}U^{238}$	α	4.51×10^9 years
Uranium X_1	Thorium 234	$_{90}Th^{234}$	β, γ	24.1 days
Uranium X_2	Protactinium 234	$_{91}Pa^{234}$	β, γ	1.18 minutes
Uranium II	Uranium 234	$_{92}U^{234}$	α	2.48×10^5 years
Ionium	Thorium 230	$_{90}Th^{230}$	α, γ	8.0×10^4 years
Radium	Radium 226	$_{88}Ra^{226}$	α, γ	1620 years
Radium emanation	Radon 222	$_{86}Rn^{222}$	α	3.82 days
Radium A	Polonium 218	$_{84}Po^{218}$	α	3.05 minutes
Radium B	Lead 214	$_{82}Pb^{214}$	β, γ	26.8 minutes
Radium C	Bismuth 214	$_{83}Bi^{214}$	β, γ	19.7 minutes
Radium C′	Polonium 214	$_{84}Po^{214}$	α	1.64×10^{-4} seconds
Radium D	Lead 210	$_{82}Pb^{210}$	β, γ	21.4 years
Radium E	Bismuth 210	$_{83}Bi^{210}$	β	5.0 days
Radium F	Polonium 210	$_{84}Po^{210}$	α, γ	138.4 days
Radium G	Lead 206	$_{82}Pb^{206}$	stable	

21.7

Each member of the series differs physically and chemically from its immediate parent or daughters; it should, therefore, be possible to separate the different members of the chain. But the separation problem was made difficult by the fact that the different radioactive species decay at different rates, some very slowly, some rapidly, others at intermediate rates. These rates and their meaning will be discussed in the next section.



An interesting example is supplied by the portion of the uranium series starting with the substance called polonium 218. A pure sample may be collected by exposing to radon a piece of ordinary material such as a thin foil of aluminum. Some of the radon atoms decay into polonium 218 atoms which are deposited on the surface of the foil. The graph at the left shows what becomes of the polonium 218. Polonium 218 decays into lead 214, which decays into bismuth 214, which decays into polonium 214, then lead 210, etc. If the original sample contains 1,000,000 atoms of polonium 218 when it is formed, after twenty minutes it will contain about 10,000 polonium 218 atoms, about 660,000 lead 214 atoms, about 240,000 bismuth 214 atoms and about 90,000 lead 210 atoms. The number of polonium 214 atoms is negligibly small because most of the polonium 214 changes into lead 210 in a small fraction of a second. The numbers of atoms of these radioactive substances change with time, quite rapidly in this particular case. A sample of pure, freshly separated radium (Ra 226) would also change in composition in a complicated way, but much more slowly. Eventually it would consist of a mixture of radium 226, radon 222, polonium 218, lead 214 and all the rest of the members of the chain down to, and including, stable "radium G" (lead). A sample of pure uranium may contain, after a time, 14 other elements of which 13—all but the last, stable portion—contribute to the radioactive emission, each in its own way. A complicated mixture of elements results and many α particles, β particles and γ rays are emitted, apparently continuously and simultaneously. SG 21.6

In 1898 the Curies obtained a total of about 200 grams of radium. Seventy years later (1968) 194 grams of this remain as radium. The six grams of radium that have been lost correspond to 16 x 10^{21} radium atoms that have decayed into radon and subsequently into other elements during these 70 years.

It is therefore evident that the separation of the different members of a radioactive chain is extremely difficult—especially if some members of the chain decay rapidly. The determination of the chemical nature and the radioactive properties of each member requires the greatest experimental ingenuity. One successful method depends on the skillful purification of a particular radioactive substance, as the Curies had done with radium and polonium. For example, suppose that a sample has been obtained from which all the radioactive substances except radium have been removed. The sample immediately starts to give off radon gas. The latter can be drawn off and its properties examined before it becomes seriously contaminated by the disintegration of many of its atoms into polonium 218. If this is done, it turns out that radon decays (through several transformations) into lead much more quickly than radium decays into radon.

Q13 Give at least 3 reasons for the difficulty of separating decay products.

21.8 Decay rate and half-life. In the last section we saw that of 1,000,000 polonium 218 atoms present in a freshly prepared sample of that radioactive substance, only about 10,000 would remain after twenty minutes, the rest having decayed into atoms of lead 214. At the end of only three minutes following preparation of the sample, fifty percent of the atoms originally present in the sample would remain, the other fifty percent having already decayed. But it would take 1620 years for half of the radium atoms in a freshly prepared sample of radium to be transformed into radon atoms. The two substances radium 226 and polonium 218 illustrate the experimental fact that radioactive elements show great differences in their rates of decay. In addition, different atoms of a given element decay at different times; some decay as soon as they are produced, while others may never decay. But, in a sample consisting of an extremely large number of any given kind of radioactive atom, it has been found experimentally that the fraction of the number of atoms of that kind that decay per second is characteristic, fixed and unchangeable; it is independent of all physical and chemical conditions, such as temperature, pressure and form of chemical combination. These remarkable properties of radioactivity deserve special attention, and the meaning of the underlined statement above will be discussed in detail because it is basic to our understanding of radioactivity.

Summary 21.8

1. Experiments showed that each radioactive nuclear species had a characteristic decay rate and hence a characteristic half-life, T.

2. The rate of decay (activity) is proportional to the number of surviving atoms.

3. The quantitative description of these facts shows the random nature of radioactive decay.

The ratio of the activity to the total number of original atoms is the fraction of the original number of atoms that has decayed per unit time. This ratio is analogous to the death rate—in the case of the United States, about 5000 persons per day in a population of 200 million, or one person per 60,000 per day.

Since the fraction of the atoms that decay per unit time is constant, the number of atoms that decay per unit time must decrease in proportion to the number of atoms remaining.

T43: Radioactive decay curve

21.8

If the number of surviving atoms is plotted as a function of time, a curve such as that shown at the left is obtained.

The curve that shows the number of atoms that have not decayed as a function of time approaches the time axis asymptotically; that is, the number of survivors becomes small but never becomes zero. This is another way of saying that we cannot assign any definite time at which the value of N falls to zero. The smaller the number of unchanged atoms, the smaller is the number that decay per unit time.

It is possible to specify the time required for any particular fraction of a sample to decay—say 1/2 or 1/3 or 37%, for instance. For convenience in making comparisons, the fraction 1/2 has been chosen. The time T required for the decay of one-half the original atoms of a pure sample, Rutherford called the half-life. Each kind of radioactive atom has a unique half-life, and thus the half-life of a substance can be used to identify a radioactive substance. As Table 21.1 shows, these half-lives vary widely.

For the parent of the uranium series, the half-life is 4.5 billion years. This means that, after 4.5×10^9 years, half of the uranium 238 atoms will have decayed. For polonium 214 the half-life is of the order of 1/10,000 of a second. If pure samples of each, containing the same number of atoms, were available, the initial activity of polonium 214 would be very strong and that of uranium 238 very feeble. If left for even a minute, though, the polonium would have decayed so rapidly and the number of the surviving atoms would be so small, that the activity due to polonium would be less than the activity of the uranium. We can speculate that some radioactive elements, present in great quantities long ago, decayed so rapidly that no measurable traces are now left. Many radioactive elements decay so slowly that during any ordinary experimentation time their decay rates seem to be constant.

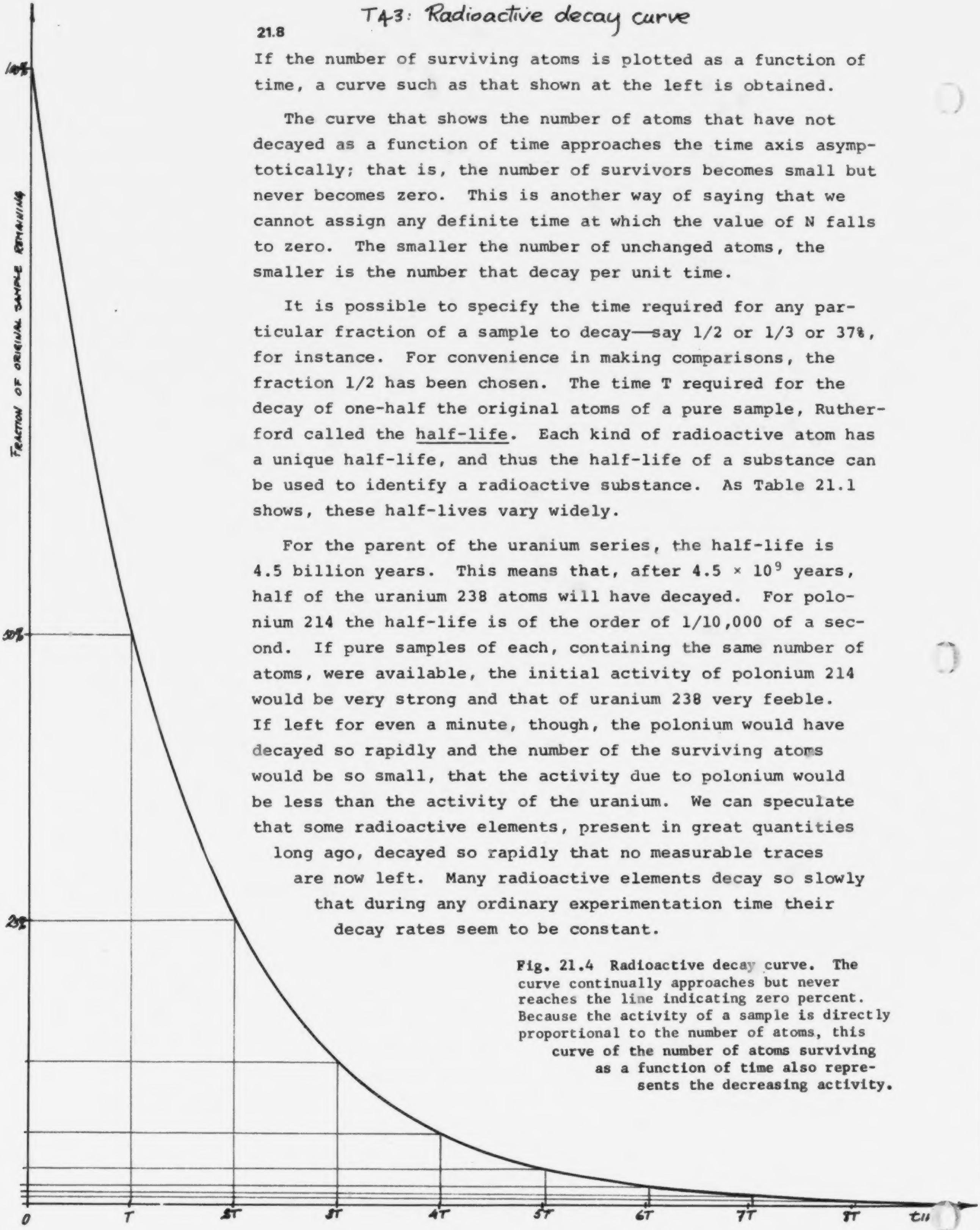


Fig. 21.4 Radioactive decay curve. The curve continually approaches but never reaches the line indicating zero percent. Because the activity of a sample is directly proportional to the number of atoms, this curve of the number of atoms surviving as a function of time also represents the decreasing activity.

The principal advantage of the concept of half-life lies in the experimental result implied in Fig. 21.4 that, no matter how old a sample with given half-life T is at a given moment, in an additional time interval T, half of the existing atoms will still survive. Thus, the half-life is not to be thought of as an abbreviation for "half a life." If one-half the original atoms remain unchanged after a time T, one-fourth (1/2 × 1/2) will remain after two consecutive half-life intervals 2T, one-eighth after 3T, and so on. Note how different the situation is for a population of, say, human beings instead of radioactive atoms. If we select a group of N_0 babies, half the number may survive to their 70th birthday; of these $N_0/2$ oldsters, none is likely to celebrate a 140th birthday. But of N_0 radioactive atoms with a half-life of 70 years, $N_0/4$ will have remained intact after 140 years, $N_0/8$ after 280 years, etc. The statistical probability of survival for atoms is unchanged by the age they have already reached; in humans, the probability of survival depends strongly on age.

SG 21.7
SG 21.8
SG 21.9
SG 21.10

We are not considering here the behavior of individual atoms, but the behavior of a very large number. If a hundred thousand persons were to flip coins simultaneously just once, we could predict with good accuracy that about one-half of them would get heads. But we could not accurately predict that one particular person in this crowd would obtain heads on a single flip. If the number of coins tossed is small, the observed count is likely to differ considerably from the prediction of 50% heads. From experiments in radioactivity we can predict that a certain fraction of a relatively large number of atoms in a sample will survive in any given time interval—say, 1/2 will survive to reach the age T—but not whether a particular atom will be among the survivors. And as the sample of survivors decreases in size owing to disintegrations, our predictions about the fraction of survivors become less accurate; finally, when only a few atoms remain unchanged, the predictions are no longer meaningful. In short, the disintegration law is a statistical law, and is thus applicable only to large populations of the radioactive atoms, not to the decay of individual atoms. It makes no assumptions as to why the atoms disintegrate. The use of this statistical law is justified because even a minute sample of a radioactive element contains very many atoms. For example, one-millionth of a gram of uranium contains 2.53 × 10^{15} atoms.

E44*: Random events

E46*: Half-life I

E47: Half-Life II

F49: Random events

In the discussion of the kinetic theory of matter we saw

The Mathematics of Decay

The beautifully simple mathematical aspect of decay is that the fraction of atoms decaying per second doesn't change with time. If initially there are N_o atoms, and a certain fraction λ[*] of them decay in one second, the number of atoms decaying in one second is λN_o. Then at any later time t, when there are only N_t atoms remaining, the fraction that decay in one second will still be λ, but the number of atoms decaying in one second is now λN_t. The constant fraction of atoms decaying per unit time is called the decay rate. The value of this rate λ can be found for each radioactive species. For example, λ for radium is 1.36×10^{-11} per second, which means that of any sample of radium atoms, on the average 0.0000000000136 of the total number in the sample will decay in one second.

This constant fractional decay rate can be represented by the following mathematic expression: $N_t = N_o e^{-\lambda t}$, or $N_t/N_o = e^{-\lambda t}$, where e is a mathematical constant = 2.718. Since the decay rate λ appears as an exponent, this expression is an "exponential" equation and is said to represent the "exponential decay" illustrated by the graph which frames p. 24.

$$N_t = N_o e^{-\lambda t}$$

$$\frac{N_t}{N_o} = e^{-\lambda t}$$

$$\log\left(\frac{N_t}{N_o}\right) = -\lambda t \log e$$

$$\text{at time T,}\quad \frac{N_t}{N_o} = \frac{1}{2}$$

$$\log\left(\frac{1}{2}\right) = -\lambda T \log e$$

$$-0.301 = -\lambda T\ (0.4343)$$

$$\lambda T = 0.693$$

The half-life T is related to the decay rate λ; the relationship can be derived as follows. We start by writing the exponential decay equation in logarithmic form. This is done by taking the logarithm of both sides of the equation. Log $(N_t/N_o) = -\lambda t \log e$. After the half-life T, the ratio $N_t/N_o = \frac{1}{2}$. So we can substitute $\frac{1}{2}$ for N_t/N_o if we substitute T for t in the equation: $\log(\frac{1}{2}) = -\lambda T \log e$. This equation can be simplified by realizing that $\log(\frac{1}{2})$ is -0.301 and $\log e = 0.4343$: $-0.301 = -\lambda T\ (0.4343)$. Thus, $\lambda T = 0.693$. We therefore find that the product of the decay rate and the half-life is always equal to 0.693.

For example, radium has a decay rate $\lambda = 1.36 \times 10^{-11}$ per second, so the half-life T of radium is $0.693/1.36 \times 10^{-11}$ per second, which is equal to 5.10×10^{10} sec or about 1690 years.

---

[*] There is no relation between the use of the symbol λ for decay rate and the use of λ for wavelength.

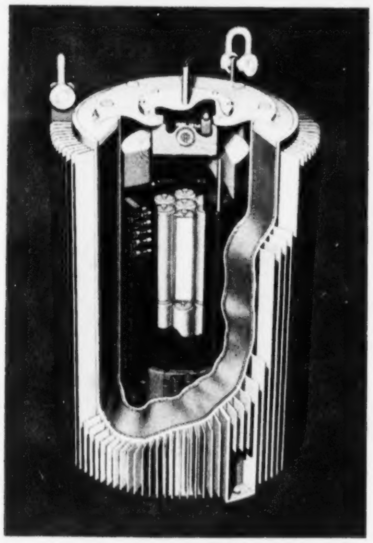
that it is a hopeless task to try to describe the motions of each individual molecule, but we could calculate the average pressure of a gas containing a very large number of molecules. Similarly, in dealing with radioactivity we find that our inability to specify when each of the tremendous number of atoms in a normal sample will disintegrate makes a statistical treatment necessary.

SG 21.11
SG 21.12

Q14 How much of a substance will be left after four of its half-lives?

Q15 If, after many many half-lives, only two atoms of a radioactive substance remain, what will happen during the next half-life?

An early SNAP (Systems for Nuclear Auxiliary Power) generator installed in a Navy Transit 4-A navigational satellite. The spontaneous fission of plutonium 238 supplies a continuous flow of heat which is converted to electricity by thermocouples.



This cutaway view of a SNAP-7 generator shows how thermocouples are arranged to convert heat from the radioactive strontium 90 cores directly to electrical energy. The outer wall is a thick metal shield designed to absorb radiation from the strontium 90, and the fins dissipate excess heat to keep the assembly at the design temperature. Most SNAP devices are built to produce a steady flow of electrical energy for a period of several years, so they are particularly adapted for use in satellites, untended lighthouses, ocean buoys and similar applications.

21.1 Which of the Curies' discoveries would have been unlikely if they had used Becquerel's photographic technique for detecting radioactivity? The radioactivity of thorium was proportional to the amount of thorium. New radioactive elements polonium and radium.

21.2 A spectroscopic examination of the γ rays from bismuth 214 shows that rays of several discrete but different energies are present. The rays are said to show a "line spectrum." The measured wavelength corresponding to one of the lines is 0.016Å.

a) Show that the energy of each of the γ-ray photons responsible for that line is 1.2×10^{-13} J. (Hint—see chapter 20.) 1.2×10^{-13} joule

b) What is the equivalent energy in electron volts? 0.75 MeV

21.3 Suppose that in Fig. 21.1 the magnetic field strength is 1.0×10^{-3} N/amp·m.

a) What would be the radius of curvature of the path of electrons entering the magnetic field with a speed of 1.0×10^{7} m/sec? (The charge and mass of the electron are 1.6×10^{-19} coul and 9.0×10^{-31} kg respectively.) 5.7×10^{-2} m

b) If α particles entered the magnetic field with the same speed as the electrons in part (a), what would be the radius of curvature of their orbit? (The mass of an α particle is 6.7×10^{-27} kg.) 420 m

c) Compare your answers to parts (a) and (b). 7350:1

21.4 If the electrons described in part (a) of the previous problem pass through crossed electric and magnetic fields as shown in the lower sketch of Fig. 21.2,

a) what must be the strength of the electric field to just balance the effect of a magnetic field of strength 1.8×10^{-3} N/amp·m? 1.0×10^{4} N/coul

b) what voltage must be supplied to the electric deflecting plates to produce the electric field strength of part (a) of this problem if the plates are 0.10 m apart? 1.0×10^{3} volts

c) what will happen to the α particles of problem 21.2 (b) moving through the crossed magnetic and electric fields of this problem? undeflected

21.5 For each part below, select the most appropriate radiation(s): α, β, or γ.

a) most penetrating radiation γ
b) most easily absorbed by aluminum foil α
c) most strongly ionizing radiation α
d) may require thick "radiation shields" for protection γ
e) cannot be deflected by a magnet γ
f) largest radius of curvature when travelling across a magnetic field α
g) highest q/m value β
h) important in Rutherford's and Royd's "mousetrap" experiment α
i) involved in the transmutation of radium to radon α
j) involved in the transmutation of bismuth 210 to polonium 210 β

21.6 Suggest an explanation for the following observations:

a) The Curies noticed in 1899 that nonradioactive substances placed near a radium compound appeared to become radioactive. Radium decayed into radon (a gas) which decays into radium A which is deposited on nearb objects.

b) William Crookes discovered in 1900 that, when a strongly radioactive uranium-containing compound was purified chemically, the uranium compound itself was left with a much smaller activity, and the separate residue containing none of the uranium was strongly radioactive.

The residue contained daughters of high activity (short half-life)

c) Becquerel found, in 1901, that in a case like (b) the uranium compound regained its original activity after several months while the residue gradually lost most of its activity during the same time. The uranium compound continually decayed into more active daughters, but the daughters in the residue were not replaced as they decayed.

21.7 A Geiger counter shows that the rate of emission of β particles from an initially pure sample of a radioactive substance decreases to one-half the initial rate in 25 hours.

a) What fraction of the original number of radioactive atoms is still unchanged at that time? $\frac{1}{2}$
b) What fraction of the original number will have disintegrated in 50 hours? $\frac{3}{4}$
c) What assumptions have you made in giving these answers? How might you check them? Assume the products of decay were not themselves radioactive.

21.8 Suppose at time t_0 a sample of pure radium consisted of 2.66×10^{21} atoms. (The half-life of radium is approximately 1600 years.)

a) If N_t is the number of radium atoms in the sample at a time t, make a graph of N_t vs. time covering a period of 8000 years.
b) Show that at the end of 8000 years, 8.3×10^{19} radium atoms still remain in the sample.
c) From your graph, estimate the number of radium atoms in the sample after 4000 years. 5.0×10^{20} atoms

21.9 The cylinder in the beaker shown and described on p. 19 reportedly contained "17,000 curies" of cobalt 60. A curie is defined as 3.70×10^{10} disintegrations per second.

a) How much energy is released per disintegration in the cobalt 60? 5.7×10^{-13} joules/ disintegration
b) What would be the rate of heat production of that cylinder after 15 years? (The half-life of cobalt 60 is approximately 5 years.)

21.10 Radioactive isotopes in quantities of 10 micro-curies or less can be purchased from the U.S. Atomic Energy Commission. How many disintegrations per second occur in a 10 micro-curie sample? 3.70×10^5 disintegration /sec

21.11 Plot the counting rate as a function of time and determine the approximate half-life of the substance having the following disintegration rates (counting rates):

Time (hr)	Counting rate (counts/min)	Time (hr)	Counting rate (counts/min)
0.0	....	6.0	1800
0.5	9535	7.0	1330
1.0	8190	8.0	980
1.5	7040	9.0	720
2.0	6050	10.0	535
3.0	4465	11.0	395
4.0	3300	12.0	290
5.0	2430		

$\lambda = 5.0 \times 10^{-3}$/min.

How many atoms decay each minute for each 10^6 atoms in the sample? (Use the relationship $\lambda T = 0.693$ derived on p. 26.) Does this number remain constant? 5×10^3 atoms/min Yes.

21.12 It takes 10 years for 10 per cent of the atoms of a fresh sample of radioactive substance to decay. How much of the 90 per cent that is left will decay in the next 10 years? 10% of the 90% or 9% of the original.

Chapter 22 Isotopes

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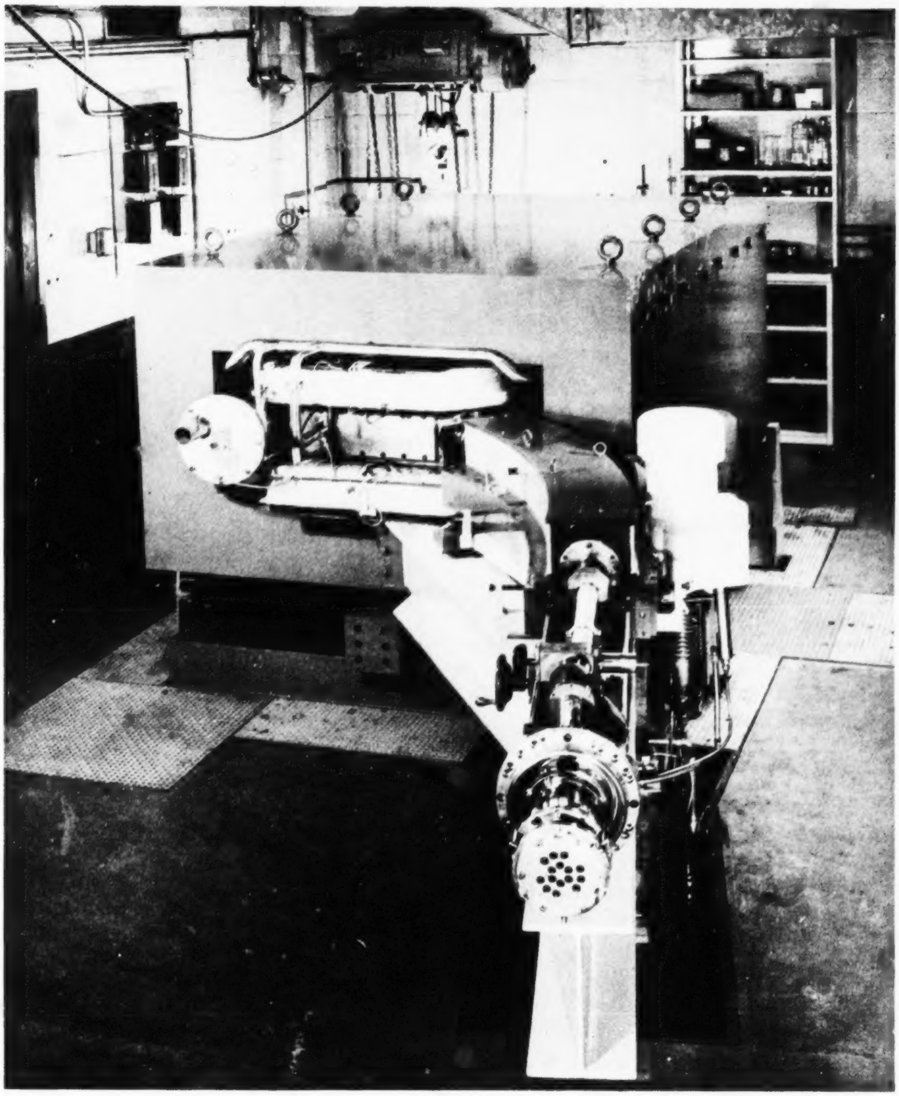


Partially assembled mass spectrograph in the laboratory of K.T. Bainbridge at Harvard University.

22.1 The concept of isotopes. The discovery that there are three radioactive series, each containing apparently new elements, raised a serious problem. In 1910 there were some empty spaces in the periodic table of the elements but there were not enough spaces for the many new elements. The periodic table represents an arrangement of the elements according to their chemical properties and, if it were unable to include the radioactive elements, it would have to be revised, perhaps in some drastic and fundamental way.

Summary 22.1
Drastic revision of the periodic table to accomodate the radioactive elements was made unnecessary by Soddy's concept of isotopes.

Soddy suggested a solution that threw a flood of light on the nature of matter and on the periodic law of the elements. The clue to the puzzle lay in the observation that some of the supposedly new elements had chemical properties identical with those of well-known elements, although some of their physical properties were different. For example, the "great-granddaughter" of uranium was found to have the same chemical properties as uranium itself. The two could not be separated by chemical means; no chemist had detected, by chemical analysis, any difference between these two substances. But they do differ from each other in certain physical properties. They are now known to be two different forms of uranium—uranium 238 and uranium 234, respectively. As Table 21.1 shows, uranium 238 and 234 have quite different half-lives: 4.5×10^9 years and 2.5×10^5 years, respectively; and the mass of a uranium 234 atom must be smaller than that of a uranium 238 atom by the mass of one α particle and two β particles. Another pair of radioactive substances, radium B and radium G, were found to have the same chemical properties as lead: when mixed with lead they could not be separated from it by chemical means. These substances are now known as lead 214 and lead 206, respectively. But lead 214 is radioactive and lead 206 is stable, and Table 21.1 shows that they must differ in mass by the mass of two α particles and four β particles. There are many other examples of such differences.

Soddy proposed that a chemical element could be regarded as a pure substance only in the sense that all of its atoms have the same chemical properties. He suggested that a chemical element may in fact be a mixture of atoms some of which have different radioactive behavior and different atomic masses but the same chemical properties. This idea meant that one of the basic postulates of Dalton's atomic theory would have to be changed, namely the postulate that the atoms of a pure element are alike in all respects. According to Soddy, it is only in chemical properties that the atoms of a given element are identical. The several physically different species of atoms making up a particular element occupy the same place in the periodic table, that is, have the same atomic number Z. Soddy called them isotopes of the element, from the Greek isos and topos meaning same and place (same place in the periodic table). Thus uranium 238 and uranium 234 are isotopes of uranium; lead 214 and lead 206 are isotopes of lead.

SG 22.1

The many species of radioactive atoms in the three radioactive series were shown by chemical analysis to be isotopes of one or another of the last eleven elements in the periodic table—from lead to uranium. For example, the second and fifth members of the uranium series were shown to be isotopes of thorium, with Z = 90; the 8th, 11th and 14th members turned out to be isotopes of polonium (Z = 84). The old symbols were therefore rewritten to represent both the chemical similarity and physical difference among isotopes. The present names, for example, are uranium 238 and uranium 234, shown in Table 21.1.

Q1 Why wasn't it necessary to expand the periodic table to fit in the newly discovered radioactive substances?

22.2 Transformation rules. Two questions then arose: how do changes in chemical nature come about in radioactive decay; and, more specifically, what determines whether the atomic number Z increases or decreases in a radioactive transformation?

Summary 22.2
The transformation rules predicted successfully the daughters of α and β decay.

In 1913, the answers to these questions were given independently by Soddy in England and by A. Fajans in Germany. They each proposed two rules we will call the transformation rules of radioactivity. Recall that by 1913 Rutherford's nuclear model of the atom was generally accepted. Using this model, one could consider a radioactive atom to have an unstable nucleus which emits an α or β particle. Every nucleus has a positive charge $+Zq_e$, where Z is the atomic number and q_e is the magnitude of the charge of an electron. The nucleus is surrounded by Z electrons which make the atom as a whole electrically neutral and determine the chemical behavior of the atom. An α particle has an atomic mass of about 4 units and a positive charge of 2 units, $+2q_e$. A β particle has a negative charge of one unit, $-q_e$, and very little mass.

The transformation rules may now be stated as follows:

(1) When a nucleus emits an α particle, the mass of the atom decreases by 4 atomic mass units and the atomic number Z of the nucleus decreases by 2 units; the resulting atom belongs to an element two spaces back in the periodic table.

Example:

$${}_{84}\mathrm{Po}^{218} \longrightarrow {}_{82}\mathrm{Pb}^{214} + \alpha .$$

(2) When a nucleus emits a β particle, the mass of the atom is practically unchanged, but the atomic number Z increases by one unit; the resulting atom belongs to an element one place forward in the periodic table. When a γ ray is emitted, there is, of course, no change in the number of atomic mass units or the atomic number.

Example:

$_{82}\text{Pb}^{214} \longrightarrow {}_{83}\text{Bi}^{214} + \beta.$

Table 21.1 shows that these rules apply to the uranium-radium series so far as the atomic number is concerned. The Rutherford-Bohr model of the atom shows why a change in chemical nature occurs as a result of α or β emission. An α particle takes two positive charges from the nucleus, and the resulting new atom can hold two fewer electrons than before in its outer shells. The new atom acts chemically like an atom of an element with an atomic number two units less than that of the atom before the radioactive change occurred. In β emission, the nucleus becomes more positively charged, by one unit. The number of electrons around the nucleus increases by one and the atom acts chemically like an atom with an atomic number one unit greater than that of the atom before the radioactive change occurred.

By using the transformation rules Soddy and Fajans were able to assign places in the periodic table to all of the radioactive elements. Each of these elements fell into a place appropriate to its chemical properties so that no revision of the periodic table was needed. Many of the positions (determined by atomic number) between Z = 82 (lead) and Z = 92 (uranium) now contained several isotopes. These results were consistent with the hypothesis of the existence of isotopes, but direct, independent evidence was also sought—and it was obtained in 1914.

SG 22.2

Q2 By how many units does the mass of an atom change during α decay? During β decay?

Q3 By how many units does the charge of a nucleus change during α decay? During β decay?

22.3 Direct evidence for isotopes of lead. Soddy knew that the stable end product of the uranium-radium series had the chemical properties of lead, and that the end product of the thorium series also had the chemical properties of lead. But he saw that these end products should have atomic masses different from that of ordinary lead (that is, lead that was not produced from a radioactive series). This result follows from a simple calculation of the change in mass as an atom decays from the starting point of a radioactive series to the end point. The calculation is simplified by ignoring beta decays in which no appreciable change in mass is involved.

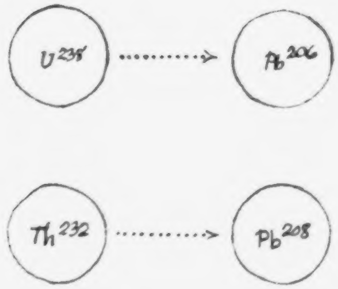
Summary 22.3

1. Experiments showed that uranium was eventually transformed into a light isotope of lead, and thorium into a heavy isotope of lead.

2. Lead 206 and ordinary lead were shown to have the similarity in properties predicted by Soddy.

3. The question arose: are other stable elements a mixture of isotopes?

22.3



In the uranium series 8 α particles, each with atomic mass of 4 units, are emitted. Hence, the end product of the series is expected to have an atomic mass close to 238 - (8 × 4) = 206 units. In the thorium series, the end product comes from thorium 232, with an atomic mass of about 232 units, and 6 α particles are emitted along the way. It should therefore have an atomic mass close to 232 - (6 × 4) = 208 units. The atomic mass of ordinary lead was known from chemical analysis to be 207.2 units. The lead extracted from the mineral thorite, which consists mainly of thorium and contains only one or two per cent by mass of uranium may be presumed to be the final product of the thorium series. The atomic mass of lead extracted from thorite should therefore be significantly different from the atomic mass of lead extracted from a uranium mineral such as pitchblende, and from the atomic mass of ordinary lead.

Here was a quantitative prediction which could be checked, and a number of chemists in Scotland, France, Germany, Austria and the United States attacked the problem. At Harvard University, T. W. Richards found atomic masses as low as 206.08 for samples of lead from ores rich in uranium. Chemists in Austria found samples of lead, in the ore uraninite, with an atomic mass of 206.04. Soddy and others found samples of lead from thorite with atomic masses as high as 207.8 and 207.9. The results left no doubt that uranium was transformed into a light isotope of lead, and thorium into a heavier isotope of lead, and that both isotopes have atomic masses different from that of ordinary lead (207.2).

Richards and his co-workers also found important similarities between ordinary lead and lead 206. The densities of these two isotopes turned out to be proportional to the respective atomic masses, which implied that the atoms of lead 206 and ordinary lead had the same volume. Furthermore, lead 206 and ordinary lead were found to have the same optical spectrum; their compounds had the same solubility in water, and the crystals of their nitrates had the same index of refraction. Hence, lead 206 and ordinary lead were shown to have properties as similar as Soddy had predicted and as Bohr's theory suggested they should be. Together, all of these results meant that the theories of radioactivity and atomic structure that were emerging in the early years of the twentieth century had passed a demanding test, and the confidence that physicists and chemists had in these theories was greatly increased.

The three forms of lead which were compared in the studies

Frederick Soddy (1877-1956), an English chemist, studied at Oxford, and went to Canada in 1899 to work under Rutherford at McGill University in Montreal. There the two worked out their explanation of radioactive decay. Soddy returned to England in 1902 to work with Sir William Ramsay, the discoverer of the rare gases argon, neon, krypton and xenon. Ramsay and Soddy showed, in 1903, that helium was continually produced by naturally radioactive substances. In 1921, Soddy was awarded the Nobel Prize in chemistry for his discovery of isotopes. He was a professor of chemistry at Oxford from 1919 to 1936.

*The normal mixture of all varieties of lead.

discussed so far, that is, ordinary lead*, lead 206 (from uranium) and lead 208 (from thorium) were all stable—not radioactive. The question immediately arose whether other stable elements are really mixtures of isotopes. In Soddy's words:

> Naturally the question was asked whether any of the common elements, for which radioactive methods of analysis are not available, are, as supposed, really homogeneous elements; and whether any are mixtures of different isotopes, with different atomic masses but with identical chemical properties, so merely appearing to be homogeneous under chemical analysis.

There are four naturally occurring lead isotopes: ${}_{82}\text{Pb}^{204}$, and the end products of three decay chains:

${}_{82}\text{Pb}^{206}$, from uranium;

${}_{82}\text{Pb}^{207}$, from actinium;

${}_{82}\text{Pb}^{208}$, from thorium.

Q4 How were the different atomic masses of lead decay-products predicted?

22.4 Positive rays. It was hard to show that stable elements may be mixtures of isotopes because isotopes cannot be separated by ordinary chemical methods. Any attempt to separate a pair of isotopes must depend on a difference in some property which depends, in turn, on the difference between their atomic masses. However, except for the very lightest elements, the difference in atomic mass is small compared to the atomic masses themselves. For the lead isotopes discussed in the last section the difference was only two units in about 200 units, or about one per cent. Any difference in a physical property between two isotopes having such a small mass difference would be expected to be very small, making separation difficult to achieve. Fortunately, when the question of the possible existence of isotopes of stable elements arose, a method was available which could answer the question. This method, developed by J. J. Thomson and extended by A. J. Dempster and others, depended on the behavior of positively charged ions when these are traveling in electric and magnetic fields.

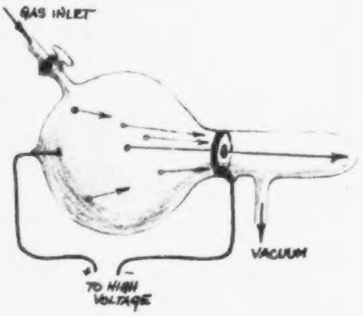
Summary 22.4
1. Separation of the isotopes of an element must be done physically, because they are identical chemically.

2. Thomson deflected positive rays in E and B fields to compare the masses of atoms

3. The modern mass spectrograph is an extremely sensitive instrument for magnetically separating isotopes and measuring their masses.

In a cathode ray tube, the electrons emitted from the cathode ionize the atoms of gas with which they collide. It was thought that the positive ions produced would accelerate toward the cathode and be neutralized there. In 1886, the German physicist Goldstein found that if holes are made in the cathode, rays pass through the cathode and emerge beyond it. Fig. 22.1 is a schematic diagram of a discharge tube for producing such rays. If the cathode fits the tube tightly, so that no gas can enter the region behind it, and if the holes are so small that very little gas can get through them, a high vacuum can be produced on the side where the rays emerge. The rays then have quite a long range and can be deflected by externally applied electric and magnetic fields.

Fig. 22.1 Discharge tube for producing a beam of positive ions. The gas between anode and cathode is ionized by the electric field. Positive ions are then accelerated toward the cathode where some of them pass through small holes and enter the well-evacuated region beyond.



J. J. Thomson (1856-1940) at work in the Cavendish Laboratory.

Thomson's apparatus used parallel electric and magnetic fields - it did not provide for selecting ions of a single speed. The positive ions of a widespread of speeds passed through the fields and formed a pattern of parabolas on a photographic plate — one parabola for each variety and speed of ions.

From the direction of the deflections it was concluded that the rays consist of positively charged particles. The rays were therefore called "positive rays" and were thought (correctly) to consist of positively charged ions of the atoms or molecules of the residual gas remaining in the discharge tube after partial evacuation.

Thomson used the positive rays from different gases to determine the relative masses of the atoms of the gases. Rather than describe the details of Thomson's early apparatus we shall describe an improved type of instrument that is in common use. This instrument typically consists of two parts: the first part provides a beam of ions all moving with the same speed; in the second part the ions pass through a magnetic field, which deflects them from a straight path into several different curved paths determined by their relative masses. Ions of different mass are thus separated to such an extent that they can be detected separately. By analogy with the instrument that separates light of different wavelengths, the instrument that separates ions of different mass was called a mass spectrograph. Its operation is explained on the opposite page. ↖developed by Aston

T45 : Mass spectrograph

D61 : Mass spectrograph

L6-2 : Thomson's positive ray parabolas

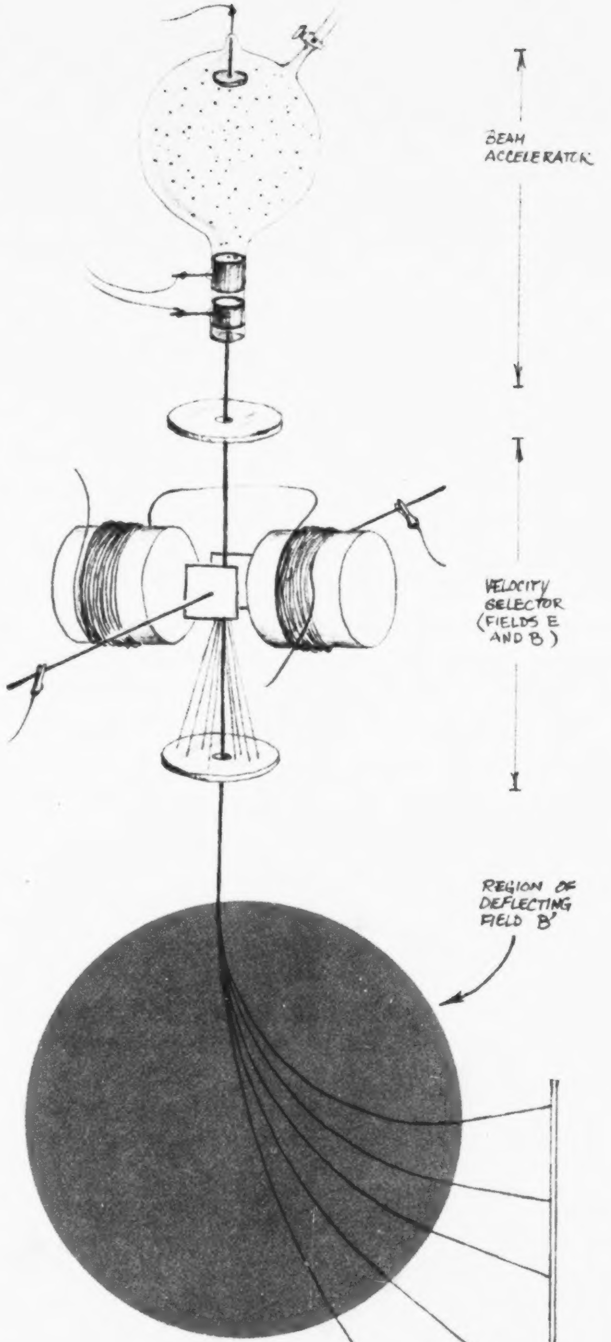
Thomson had obtained results from measurement of $\frac{q}{m}$ for positive rays which were quite different from those obtained for cathode ray particles or β particles. Both the speeds and $\frac{q}{m}$ were found to be smaller for gases with heavier molecules. These results are consistent with the idea that the positive rays are streams of positively ionized atoms or molecules.

Can the values of q and m be separately determined? The magnitude of q must be a multiple of the electron charge q_e, that is, it can only be q_e, or $2q_e$, $3q_e$, $4q_e$,.... The greater the charge, the greater the magnetic force will be and, therefore, the more curved the path of the ions. In the apparatus of Fig. 22.2 a doubly ionized atom (an ion with charge $+2q_e$) will follow a path with half the radius of that of a singly ionized atom of similar type, a triply ionized atom will trace out a semi-circular path with one-third the radius, etc. Thus, for each type of atom analyzed, the path with the largest radius will be that taken by the ions with the single charge q_e. Since q is known for each path, the mass of the ions can be determined from the known values of q/m.

Some mass spectrometers are portable; small ones similar to this are carried aloft for analysis of the upper atmosphere.

The study of positive rays with the mass spectrograph made it possible to measure for the first time the masses of individual atoms. With the methods used before, it was possible to obtain only average masses for very large numbers of atoms.

Fig. 22.2 The principle of the mass spectrograph.


BEAM ACCELERATOR
VELOCITY SELECTOR (FIELDS E AND B)
REGION OF DEFLECTING FIELD B'
PHOTOGRAPHIC PLATE (OR ION CURRENT DETECTOR)

The magnetic separation of isotopes begins by electrically charging the atoms of a sample of material, for example by means of an electric discharge through a sample of gas. The resulting ions are then accelerated into a beam by an electric potential difference.

Before the different isotopes in the beam are separated, there is usually a preliminary stage that allows only those ions with a certain velocity to pass through. In one type, the ion beam initially enters a region of crossed magnetic fields $\vec{B}$ and $\vec{E}$, where each ion experiences a magnetic force of magnitude qvB and an electric force of magnitude qE. The magnetic and electric forces act on an ion in opposite directions, and only for ions of a certain speed will the forces be balanced, allowing them to pass straight through the crossed fields. For these ions $qvB = qE$, and so their speed $v = E/B$. Because only ions with this speed in the original direction remain in the beam, this part of the apparatus is called a velocity selector.

The separation of isotopes is then accomplished by a magnetic field B'. As the beam enters this field, the magnetic force acts as a centripetal force to cause each ion to move in a circular arc whose radius R depends upon the ion's charge-to-mass ratio. That is $qvB' = mv^2/R$ and so $q/m = v/B'R$.

The divided beams of ions fall on either a photographic plate (in a mass spectrograph) or a sensitive electrometer probe (in a mass spectrometer), allowing the radii of their deflections to be calculated from the geometry of the apparatus. Since v, B' and R can be determined from measurements; the charge-to-mass ratio of each velocity of ions in the beam can be calculated.

The uncertainty of mass determinations made with modern mass spectrographs can be less than one part in a hundred thousand, that is, less than 0.001 percent. The difference in the masses of the isotopes of an element is never less than about 0.3 percent, and so is easily detected.

Q5 The curvature of an ion beam in a magnetic field depends on both the mass and speed of the ions. How then can a mass spectograph make precise separation by mass?

Summary 22.5

1. Thomson showed that isotopes exist for neon, an ordinary (non-radioactive) element

2. Aston used gaseous diffusion techniques and his mass spectrograph to verify that neon has two isotopes.

3. Aston showed that other elements have isotopes and by measuring their "mass spectra", he calculated many isotopic masses.

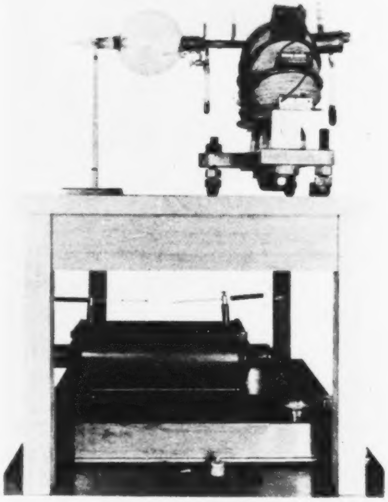
22.5 Separating Isotopes. In Thomson's original instrument the error was about one per cent, but this was small enough to permit Thomson to make the first observation of separated isotopes. He introduced a beam of neon ions from a discharge tube containing chemically pure neon into his mass spectrograph. The atomic mass of neon had been determined as 20.2 atomic mass units by means of the usual methods for determining the atomic (or molecular) mass of a gas. At about the position on the photographic plate where ions of atomic mass 20 were expected to arrive, a dark line was observed when the plate was developed. But, in addition, there was also present a faint line such as would indicate the presence of particles with atomic mass 22. No chemical element or gaseous compound was known which had this atomic or molecular mass. The presence of this line suggested, therefore, that neon might be a mixture of one form, or isotope, with atomic mass 20 and another isotope with atomic mass 22. The average chemical mass 20.2 would result if neon contained about ten times as many atoms of atomic mass 20 as of atomic mass 22.

The evidence that neon has two isotopes was so striking that Thomson's associate, F. W. Aston, looked for further evidence that might bear on this problem. It was well known from kinetic theory that in a mixture of two gases with different molecular masses the lighter molecules have a higher average speed than the heavier molecules. The lighter molecules, therefore, collide more often with the walls of a container than do the heavier molecules. If the mixture is allowed to diffuse through a porous wall from one container into another, the heavier molecules are less likely to pass through than the lighter, faster ones. The gas that does not get through the wall will, therefore, have more of the heavier molecules than the gas that does pass through the wall.

Aston allowed part of a sample of chemically pure neon gas to pass through such a wall. One pass accomplished only a slight separation of the lighter and heavier molecules, so a portion of the gas which had passed through the wall was

Francis William Aston (1877-1945) studied chemistry at the University of Birmingham. In 1910 he went to Cambridge to work under J. J. Thomson. He was awarded the Nobel Prize in chemistry, in 1922, for his work with the mass spectrograph. In disagreement with Rutherford, Aston pictured a future in which the energy of the atom would be tapped by man. In his Nobel acceptance speech he also spoke of the dangers involved in such a possibility. Aston lived just long enough—by three months—to learn of the explosion of the nuclear bombs.

passed through the wall again, the process was repeated many times. He measured the atomic mass of each fraction of the gas and found values of 20.15 atomic mass units for the fraction that had passed through the wall many times and 20.28 units for the fraction that had been left behind many times. The difference in average atomic mass indicated that the neon was, indeed, a mixture of isotopes. Even more impressive was the change in the relative intensities of the two traces (for the masses 20 and 22) in the mass spectrograph. The line corresponding to mass 22 was more prominent in the analysis of the fraction of the gas that had been left behind, showing that this fraction was "enriched" in atoms of mass 22. Although the separation of the two isotopes was not complete, it was clear that there are two isotopes of neon, one with atomic mass 20, the other with atomic mass 22. The optical emission spectrum of the enriched sample was the same as that of the original neon sample—proving that no substance other than neon was present.



Side view of one of Aston's earlier mass spectrographs.

SG 22.3

L6-3: Aston's mass spectrograph

These results encouraged Aston to improve the design of the mass spectrograph and determine the atomic masses of many elements. He found that other elements also were made up of isotopes. The atomic masses of the isotopes of the naturally occurring elements have now been determined. Figure 22.3 shows the mass spectrograph record obtained for germanium, indicating that this element has five isotopes. Pictures of this kind are called "mass spectra."

Although we cannot measure the mass of a neutral atom in a mass spectrograph (why not?), we usually list isotopic masses for neutral atoms.

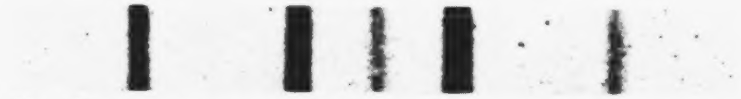


Fig. 22.3 The mass spectrum of germanium, showing the isotopes of mass numbers 70, 72, 73, 74, 76.

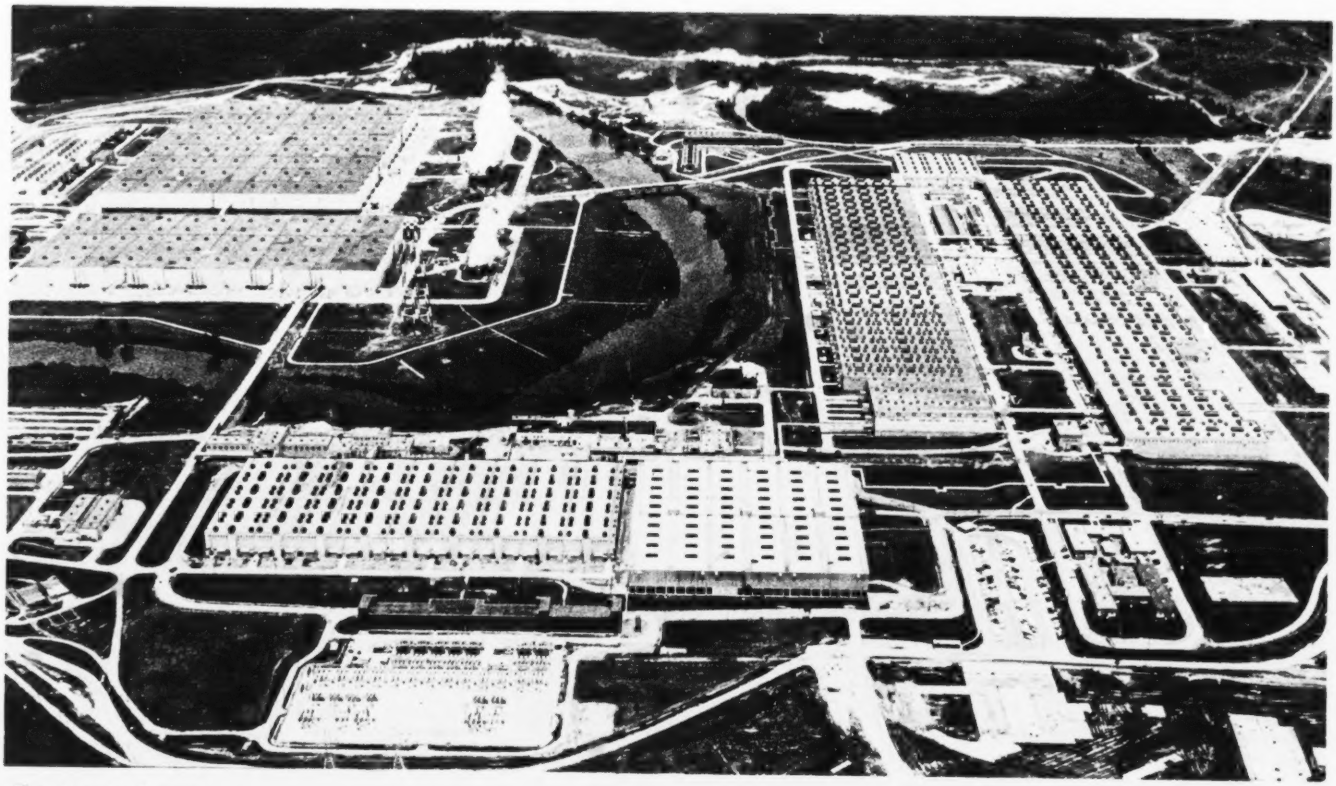
SG 22.4

Both the electromagnetic and gas-diffusion methods of separating isotopes have been modified for large-scale applications. The electromagnetic method is used by the United States Atomic Energy Commission to provide samples of separated isotopes for research. The method used by Aston in achieving a small degree of separation of the neon isotopes has been developed on an enormous scale to separate the isotopes of uranium in connection with the manufacture of nuclear bombs and the production of nuclear power.

D62 : Aston analog

Q6 What were 3 experimental results which supported the belief in two isotopes of neon?

Q7 Isotopes are separated in a mass spectograph because more massive ions are deflected less. Why are isotopos separated in diffusing through a porous wall?



The Atomic Energy Commission's Gaseous Diffusion Plant at Oak Ridge, Tennessee. The long buildings right of center made up the first plant.

Summary 22.6

1. Both atomic number Z and mass number A are used to specify a particular atomic species, or nuclide.

2. In equations representing nuclear reactions, the mass numbers balance and the atomic numbers balance.

22.6 A useful notation for nuclides and nuclear reactions. It will be useful to summarize some ideas and notations. Because of the existence of isotopes it was no longer possible to designate an atomic species by means of the atomic number Z alone. To distinguish among the isotopes of an element some new symbols were introduced. One is the mass number, A, defined as the whole number closest to the measured atomic mass (see Table 22.1). For example, the lighter and heavier isotopes of neon are characterized by the pairs of values: $Z = 10$, $A = 20$, and $Z = 10$, $A = 22$, respectively. An element which consists of a single atomic species can, of course, also be characterized by its Z and A values. These values are determined by the properties of the atomic nucleus: according to the Rutherford-Bohr model of the atom, the atomic number Z is the magnitude of the positive charge of the nucleus in elementary charge units. The mass number A is very nearly equal to the atomic mass of the nucleus (expressed in atomic mass units) because the total electron mass is very small compared to the mass of the nucleus. The term nuclide is used to denote an atomic species characterized by particular values of Z and A. An isotope is then one of a group of two or more nuclides having the same atomic number Z but different mass numbers A. A radioactive atomic species is a radioactive nuclide, or radionuclide for short. A nuclide is usually denoted by the chemical symbol with a subscript at the lower left giving the atomic number, and a superscript at the upper right giving the mass number. *In the symbol* ${}_ZX^A$ for a nuclide, Z is the atomic number, X is the chemical symbol and A is the mass number. For example, ${}_4Be^9$ is the nuclide beryllium with atomic number 4 and mass number 9; the symbols ${}_{10}Ne^{20}$ and ${}_{10}Ne^{22}$ represent the neon isotopes discussed above. The Z-value is the same for all the isotopes of a given element (X), and so is often omitted—except when it is needed for balancing equations (as you will shortly see). Thus, we often write O^{16} for ${}_8O^{16}$, or Ne^{20} for ${}_{10}Ne^{20}$ or U^{238} for ${}_{92}U^{238}$.

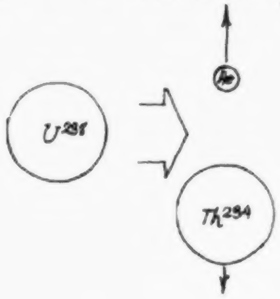
The introduction of the mass number and the symbol for a nuclide makes it possible to designate the radioactive nuclides in an easy and consistent way, as was shown in Table 21.1. Radioactive decay can be expressed by a simple equation representing the changes that occur in the decay process. The first step in the uranium-radium series, the decay of uranium 238 into thorium 234, may be written:

$$ {}_{92}U^{238} \xrightarrow{\text{decays into}} {}_{90}Th^{234} + {}_2He^4. $$

The symbol ${}_2He^4$ stands for the helium nucleus (α particle); the other two symbols represent the initial and final atomic nuclei, each with the appropriate charge and mass number. The equation represents a nuclear reaction, and is analogous to an equation for a chemical reaction. The atomic numbers on the two sides of the equation must balance because the electric charge of the nucleus must be conserved: 92 = 90 + 2. Also, the mass numbers must balance because of conservation of mass: 238 = 234 + 4. We see from Table 21.1 that ${}_{90}Th^{234}$ (thorium 234) decays to ${}_{91}Pa^{234}$ (protactinium 234) with the emission of a β particle. Since a β particle (electron) has charge $-q_e$ and has an extremely small mass, the symbol ${}_{-1}e^0$ is used for it. This β decay process may then be represented by the equation:

$$ {}_{90}Th^{234} \xrightarrow{\text{decays into}} {}_{91}Pa^{234} + {}_{-1}e^0 + \bar{\nu} $$

F48: U^{238} radioactivity series



There is also an antineutrino ($\bar{\nu}$) given off together with the β particle. The neutrino and antineutrino are two particles which will be discussed briefly in Sec. 23.6.

SG 22.5

SG 22.6

SG 22.7

SG 22.8

Q8 Write the complete symbol for the nuclide with atomic mass 194 and atomic number 78. Of what element is it an isotope?

Q9 Complete the following equation for α-decay:

$$ {}_ZX^A \longrightarrow {}_2He^4 + {}_{Z-2}X^? $$

Q10 Complete the following equation for β-decay:

$$ {}_ZX^A \longrightarrow {}_{-1}e^0 + {}_?X^A $$

Table 22.1 Relative natural abundances and masses of some nuclides

The masses are given in atomic mass units (amu) based on ${}_{6}C^{12}$ = 12.000 000

Element	Chemical Symbol	Atomic Number Z	Mass Number A	Relative Abundance %	Mass of Neutral Atom (amu)
Hydrogen	H	1	1	99.98	1.007825
		1	2	0.02	2.014102
Helium	He	2	4	100.00	4.002604
Lithium	Li	3	6	7.42	6.015126
		3	7	92.58	7.016005
Beryllium	Be	4	9	100.00	9.012186
Carbon	C	6	12	98.89	12.000000
		6	13	1.11	13.003354
Nitrogen	N	7	14	99.63	14.003074
		7	15	0.37	15.000108
Oxygen	O	8	16	99.76	15.994915
		8	17	0.04	16.999134
		8	18	0.20	17.999160
Neon	Ne	10	20	90.92	19.992440
		10	21	0.26	20.993849
		10	22	8.82	21.991385
Aluminum	Al	13	27	100.00	26.981535
Chlorine	Cl	17	35	75.53	34.968855
		17	37	24.47	36.965896
Platinum	Pt	78	190	0.01	189.9600
		78	192	0.78	191.9614
		78	194	32.90	193.9628
		78	195	33.80	194.9648
		78	196	25.30	195.9650
		78	198	7.21	197.9675
Gold	Au	79	197	100.00	196.9666
Lead	Pb	82	204	1.50	203.9731
		82	206	23.60	205.9745
		82	207	22.60	206.9759
		82	208	52.30	207.9766
Thorium	Th	90	232	100.00	232.0382
Uranium	U	92	234	0.006	234.0409
		92	235	0.720	235.0439
		92	238	99.274	238.0508

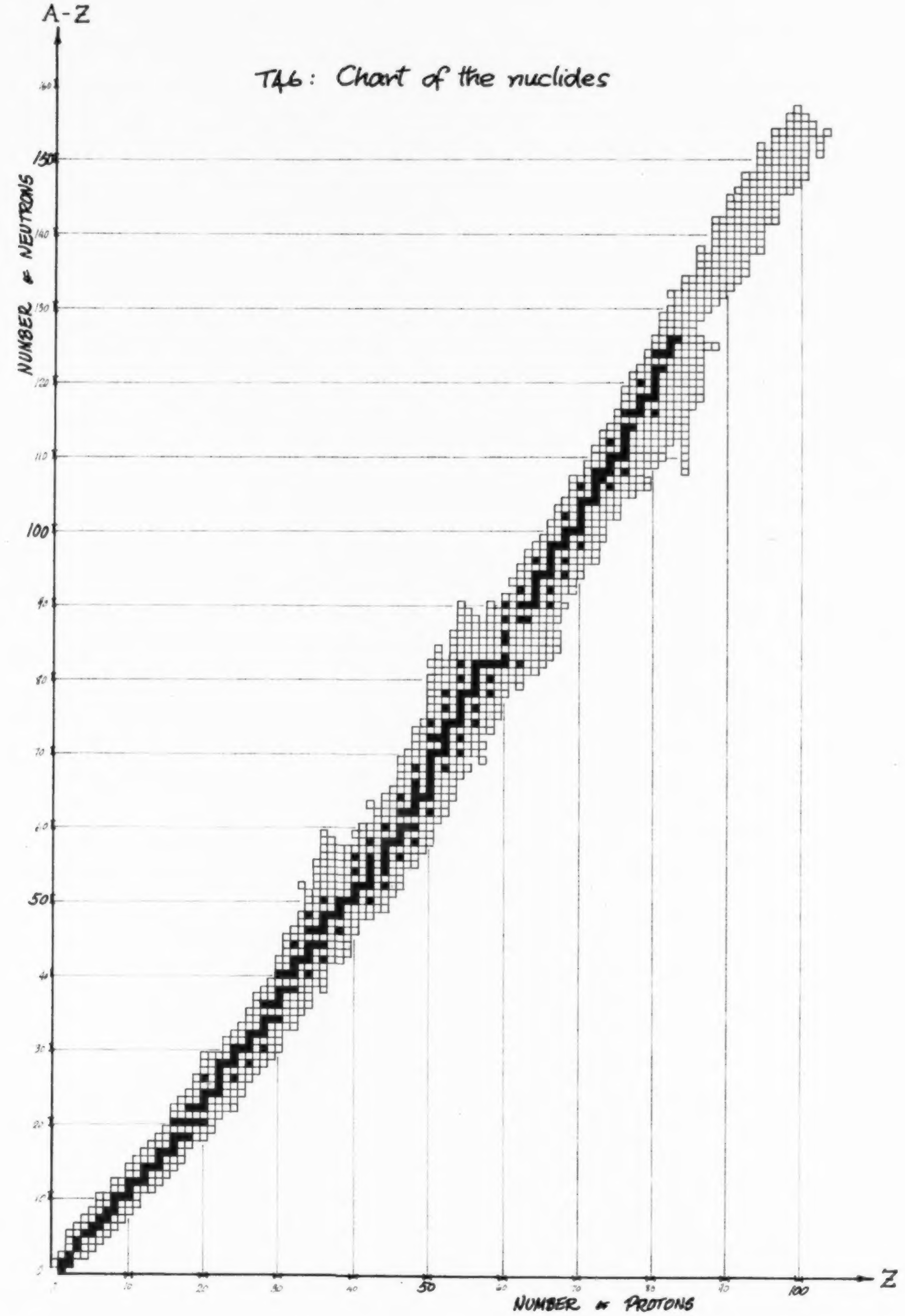


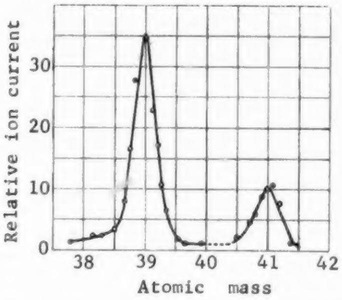
Chart of the known nuclides. Each black square represents a stable nuclide, each open square represents an unstable nuclide. All isotopes of a given element are found in a vertical column centered on the element's atomic number Z. (As will be seen in the next chapter, the Z number is the number of protons in the nucleus, and A - Z, the difference between the atomic mass and atomic number, is the number of neutrons.)

22.7 __The stable isotopes of the elements and their relative abundances__. Mass spectra, such as the one of germanium shown in *Fig. 22.3 have been determined for all* the elements with at least one stable nuclide. These are the elements with atomic numbers between 1 (hydrogen) and 83 (bismuth). A few of the results are listed in Table 22.1. The table also includes the unstable (radioactive) elements uranium and thorium because they have such long half-lives that they are still present in large quantities in some rocks. Uranium has three naturally occurring isotopes, one of which, U^{235}, has remarkable nuclear properties that have made it important in military and political affairs as well as in science and industry. As can be seen in Table 22.1, the relative abundance of U^{235} is very low and it must first be separated from the far more abundant U^{238} before it can be used in practical applications. Such applications and some of their social effects will be discussed in Chapter 24.

Summary 22.7
1. Mass spectra of the stable elements, from Z = 1 to Z = 83, show that they comprise 284 naturally occurring nuclides. (The chart of the nuclides on page 44 shows them, and table 22.1 gives the relative abundances of some selected nuclides.)

2. There are regularities in the abundances which have implications for models of the nucleus.

Of the elements having atomic numbers between 1 and 83, only about one-fourth of them are single species, the others all have two or more isotopes. As a result, the 83 elements actually consist of 284 naturally occurring nuclides. All but 25 of these nuclides are stable. Many elements have only one stable nuclide, others have several and tin has the greatest number, ten. Carbon and nitrogen each have two and oxygen has three. (Table 22.1 shows that the isotope O^{16} has a very high relative abundance; the isotopes O^{17} and O^{18} being relatively rare.)



Detection of the isotopes of potassium in a mass spectrometer. In a mass spectrometer the current due to the ions is detected. Comparison of the current due to each isotope permits fairly precise estimates of the relative abundances of the isotopes.

The 25 naturally occurring unstable nuclides show a very small degree of radioactivity; they are not associated with the decay chains of the heavy radionuclides and have activities which are generally much feebler. The most common of these light nuclides is ${}_{19}K^{40}$, an isotope of potassium that has a relative abundance of only 0.012%. This isotope, which emits β particles, has a long half-life (1.3 × 10^9 years) which makes it extremely useful for determining the ages of certain rocks. Such information, coupled with information on the decay of U^{238}, can be used to estimate the age of the earth.

SG 22.9

Hydrogen, the lightest element, has two stable isotopes, of which the heavier one, with mass number 2, has a relative abundance of only 0.02%. The hydrogen isotopes are exceptional in that the rare isotope has an atomic mass twice that of the common isotope. As a result, the differences between the properties of the two isotopes are more marked than in any other pair of isotopes. The hydrogen isotope of mass 2 has therefore been given its own name, deuterium, with the

F50: Long time intervals

D60: Naturally occurring radioactivity

symbol D; sometimes it is called "heavy hydrogen." There is a kind of water, called "heavy water" or "deuterium oxide," with the formula $({}_1H^2)_2O$ or D_2O. Heavy water differs from ordinary water in some important respects: its density is 1.11 gram per cm^3 as compared with 1.00 for ordinary water; it freezes at 3.82°C and boils at 101.42°C, the corresponding temperatures for ordinary water being 0°C and 100°C, respectively. Naturally occurring water contains only about 1 atom of H^2 per 7000 atoms of H^1, but methods have been developed for producing nearly pure D_2O in large amounts. Heavy water is important in some types of devices for the controlled release of nuclear energy, as will be explained in Chapter 24.

H. C. Urey received the 1934 Nobel Prize in chemistry for his discovery of "heavy" hydrogen.

Some interesting and important regularities have been found among the natural abundances. The number of nuclides with the various combinations of even and odd values of Z and A are listed in Table 22.2. It is evident that nuclides with even Z and even A are much more numerous than those with any other combination. Elements with even Z have, on the average, more isotopes per element than those with odd Z. Any theory of the nucleus will have to account for these regularities, which are related to the stability of atomic nuclei. Information of this kind is analogous to observations of the positions of planets, to data on chemical compounds and to atomic spectra. All of these provide material for the building of theories and models.

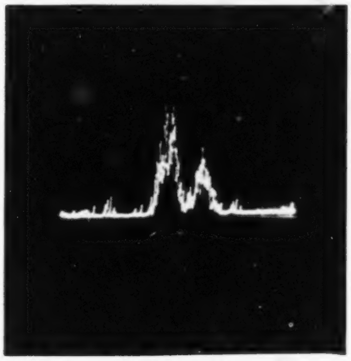
Table 22.2 Some Interesting Data Concerning Nuclides

		Number of Nuclides			
	Number of Stable Elements	with Odd A	with Even A	Total	Avg. Number of Isotopes Per Element
Odd Z	40	53	8	61	1.5
Even Z	43	57	166	223	5.2
Total	83	110	174	284	3.4

Q11 What is deuterium?

Q12 Neon actually has three isotopes (see Table 22.1). Why did Thomson and Aston find evidence for only two isotopes?

22.8 Atomic masses. The masses of most of the stable nuclides have been determined and the results are of fundamental importance in quantitative work in nuclear physics and its applications. The standard of mass adopted by physicists for expressing the atomic mass of any nuclide was slightly different from that used by chemists for the chemical atomic



This is a photograph of the oscilloscope display of a high-resolution mass spectrometer. The high peak, on the left, indicates the He^3 isotope of mass 3.016030 amu. The other peak indicates H^3, the extra heavy hydrogen isotope, otherwise known as tritium, whose mass is 3.016049 amu. The mass difference is therefore about one part in 150,000.

Summary 22.8
1. Atomic masses are usually expressed in amu based on carbon 12 = 12.000000 amu

2. The relative masses of all nuclides are within 0.06 of whole numbers.

weights. The chemists' scale was defined by assigning the value 16.0000 atomic mass units to ordinary oxygen. But, as can be seen in Table 22.1, oxygen is a mixture of three isotopes, two of which, O^{17} and O^{18}, have very small abundances. For isotopic mass measurements, the value 16.0000 was assigned to the most abundant isotope, O^{16}, and this mass was used as the standard by physicists. For some years, up to 1960, the atomic mass unit, 1 amu, was defined as 1/16 of the mass of a neutral O^{16} atom. Since 1960, ${}_8O^{16}$ has been replaced by ${}_6C^{12}$ as the standard, and the atomic mass unit is now defined by both physicists and chemists as 1/12 of the mass of a neutral C^{12} atom. The main reason for the choice of carbon is that mass-spectrographic measurements of atomic masses are much more accurate than the older chemical methods. Carbon forms an exceptional variety of compounds, from light to very heavy, which can be used as comparison standards in the mass spectrograph.

SG 22.10
SG 22.11

The results obtained for the atomic masses of some elements of special interest are listed in Table 22.1. Atomic masses can be determined with great accuracy and, when expressed in atomic mass units, all turn out to be very close to integers. The mass differs from an integer by less than 0.06 amu for each nuclide. This result is known as Aston's whole-number rule and provides the justification for using the mass number in the symbol ${}_ZX^A$ for a nuclide or atom. The physical basis for this rule is connected with the structure of the nucleus and will be discussed in the next chapter.

Q13 What nuclide is the current standard for atomic mass?

List of the Elements

Element	Symbol	Atomic Number	Year of Isolation or Discovery and Origin of Name*
Actinium	Ac	89	1900 Greek aktis, ray
Aluminum	Al	13	1825 Latin alumen, substance with astringent taste
Americium	Am	95	1944 America
Antimony	Sb	51	15th century, Greek antimonos, opposite to solitude
Argon	Ar	18	1894 Greek argos, inactive
Arsenic	As	33	13th century, Greek arsenikon, valiant
Astatine	At	85	1940 Greek astatos, unstable
Barium	Ba	56	1808 Greek barys, heavy
Berkelium	Bk	97	1949 Berkeley, California
Beryllium	Be	4	1797 mineral, beryl
Bismuth	Bi	83	15th century, German weisse masse, white mass
Boron	B	5	1808 Arabic bawraq, white
Bromine	Br	35	1826 Greek bromos, a stench
Cadmium	Cd	48	1817 Latin cadmia, calamine, a zinc ore
Calcium	Ca	20	1808 Latin calcis, lime
Californium	Cf	98	1950 State & University of California
Carbon	C	6	prehistoric, Latin carbo, coal
Cerium	Ce	58	1804 the asteroid Ceres discovered 1803
Cesium	Cs	55	1860 Latin caesius, sky blue
Chlorine	Cl	17	1808 Greek chloros, grass green
Chromium	Cr	24	1797 Greek chroma, color
Cobalt	Co	27	1735 Greek kobolos, a goblin
Copper	Cu	29	prehistoric, Latin cuprum, copper
Curium	Cm	96	1944 Marie and Pierre Curie
Dysprosium	Dy	66	1886 Greek dysprositos, hard to get at
Einsteinium	Es	99	1952 Albert Einstein
Erbium	Er	68	1843 Ytterby, a town in Sweden
Europium	Eu	63	1900 Europe
Fermium	Fm	100	1953 Enrico Fermi
Fluorine	F	9	1886 Latin fluere, to flow
Francium	Fr	87	1939 France
Gadolinium	Gd	64	1886 Johan Gadolin, Finnish chemist
Gallium	Ga	31	1875 Gaul, or France
Germanium	Ge	32	1886 Germany
Gold	Au	79	prehistoric, Anglo-Saxon gold, symbol from Latin aurum
Hafnium	Hf	72	1922 Hafnia, Latin for Copenhagen
Helium	He	2	1895 Greek helios, the sun
Holmium	Ho	67	1879 Holmia, Latin for Stockholm
Hydrogen	H	1	1766 Greek hydro genes, water former
Indium	In	49	1863 indigo-blue spectrum line
Iodine	I	53	1811 Greek iodes, violet-like
Iridium	Ir	77	1804 Latin iridis, rainbow
Iron	Fe	26	prehistoric, Anglo-Saxon iren or isen, symbol from Latin ferrum
Krypton	Kr	36	1898 Greek kryptos, hidden
Lanthanum	La	57	1839 Greek lanthanien, to be concealed
Lawrencium	Lw	103	1961 Ernest O. Lawrence, inventor of cyclotron
Lead	Pb	82	Prehistoric, middle English led, symbol from Latin plumbum
Lithium	Li	3	1817 Greek lithos, stone
Lutetium	Lu	71	1905 Lutetia, ancient name of Paris
Magnesium	Mg	12	1774 Latin magnes, magnet
Mendelevium	Md	101	1955 Dmitri Mendeleev, who devised first Periodic Table
Mercury	Hg	80	prehistoric, Latin Mercurius, the god and planet
Molybdenum	Mo	42	1782 Greek molybdos, lead
Neodymium	Nd	60	1885 Greek neos, new, and didymos, twin
Neon	Ne	10	1898 Greek neos, new
Neptunium	Np	93	1940 planet Neptune
Nickel	Ni	28	1750 German Nickel, a goblin or devil
Niobium	Nb	41	1801 Niobe, daughter of Tantalus
Nitrogen	N	7	1772 Latin nitro, native soda, and gen, born
Nobelium	No	102	1957 Alfred Nobel
Osmium	Os	76	1804 Greek osme, a smell, from the odor of its volatile tetroxide
Oxygen	O	8	1774 Greek oxys, sharp, and gen, born
Palladium	Pd	46	1803 planetoid Pallas, discovered 1801
Phosphorus	P	15	1669 Greek phosphoros, light bringer
Platinum	Pt	78	1735 Spanish plata, silver
Plutonium	Pu	94	1940 Pluto, the second trans-Uranus planet

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*adapted from Alfred Römer, The Restless Atom, Science Study Series, Doubleday Co., N.Y.

Polonium	Po	84	1898	Poland, country of discoverer
Potassium	K	19	1807	English potash, symbol Latin kalium
Praseodymium	Pr	59	1885	Greek praseos, leek green, and didymos, a twin
Promethium	Pm	61	1947	Prometheus, fire bringer of Greek mythology
Protactinium	Pa	91	1917	Greek protos first, and actinium because it disintegrates into it
Radium	Ra	88	1898	Latin radius, ray
Radon	Rn	86	1900	because it comes from radium
Rhenium	Re	75	1924	Latin Rhenus, Rhine province of Germany
Rhodium	Rh	45	1804	Greek rhodon, a rose
Rubidium	Rb	37	1860	Latin rubidus, red
Ruthenium	Ru	44	1845	Latin Ruthenia, Russia
Samarium	Sm	62	1879	Samarski, a Russian engineer
Scandium	Sc	21	1879	Scandinavian peninsula
Selenium	Se	34	1817	Greek selene, moon
Silicon	Si	14	1823	Latin silex, flint
Silver	Ag	47	prehistoric, Anglo-Saxon seolfor, symbol from Latin argentum	
Sodium	Na	11	1807	Medieval Latin soda, symbol from Latin natrium
Strontium	Sr	38	1808	town of Strontian, Scotland
Sulfur	S	16	prehistoric, Latin sulphur	
Tantalum	Ta	73	1802	Tantalus of Greek mythology
Technetium	Tc	43	1937	Greek technetos, artificial
Tellurium	Te	52	1782	Latin tellus, the earth
Terbium	Tb	65	1843	Ytterby, town in Sweden
Thallium	Tl	81	1862	Greek thallos, a young shoot
Thorium	Th	90	1819	Scandinavian mythology, Thor
Thulium	Tm	69	1879	Latin Thule, most northerly part of the habitable world
Tin	Sn	50	prehistoric, origin of name unknown, symbol Latin stannum	
Titanium	Ti	22	1791	Greek mythology, Titans, first sons of the earth
Tungsten	W	74	1783	Swedish tung sten, heavy stone, symbol from the mineral wolframite
Uranium	U	92	1789	Planet Uranus
Vanadium	V	23	1830	goddess Vanadis of Scandinavian mythology
Xenon	Xe	54	1898	Greek xenos, strange
Ytterbium	Yb	70	1905	Ytterby a town in Sweden
Yttrium	Y	39	1843	Ytterby a town in Sweden
Zinc	Zn	30	prehistoric, German Zink, akin to Zinn, tin	
Zirconium	Zr	40	1824	Arabian Zerk, a precious stone

Periodic Table of the Elements

Group→ Period ↓	I	II											III	IV	V	VI	VII	0
1	1.0080 H 1																	4.0026 He 2
2	6.939 Li 3	9.012 Be 4											10.811 B 5	12.011 C 6	14.007 N 7	15.999 O 8	18.998 F 9	20.183 Ne 10
3	22.990 Na 11	24.31 Mg 12											26.98 Al 13	28.09 Si 14	30.97 P 15	32.06 S 16	35.45 Cl 17	39.95 Ar 18
4	39.10 K 19	40.08 Ca 20	44.96 Sc 21	47.90 Ti 22	50.94 V 23	52.00 Cr 24	54.94 Mn 25	55.85 Fe 26	58.93 Co 27	58.71 Ni 28	63.54 Cu 29	65.37 Zn 30	69.72 Ga 31	72.59 Ge 32	74.92 As 33	78.96 Se 34	79.91 Br 35	83.80 Kr 36
5	85.47 Rb 37	87.62 Sr 38	88.91 Y 39	91.22 Zr 40	92.91 Nb 41	95.94 Mo 42	(99) Tc 43	101.07 Ru 44	102.91 Rh 45	106.4 Pd 46	107.87 Ag 47	112.40 Cd 48	114.82 In 49	118.69 Sn 50	121.75 Sb 51	127.60 Te 52	126.9 I 53	131.30 Xe 54
6	132.91 Cs 55	137.34 Ba 56	* 57–71	178.49 Hf 72	180.95 Ta 73	183.85 W 74	186.2 Re 75	190.2 Os 76	192.2 Ir 77	195.09 Pt 78	196.97 Au 79	200.59 Hg 80	204.37 Tl 81	207.19 Pb 82	208.98 Bi 83	210 Po 84	(210) At 85	222 Rn 86
7	(223) Fr 87	226.05 Ra 88	† 89															

*Rare-earth metals	138.91 La 57	140.12 Ce 58	140.91 Pr 59	144.27 Nd 60	(147) Pm 61	150.35 Sm 62	151.96 Eu 63	157.25 Gd 64	158.92 Tb 65	162.50 Dy 66	164.93 Ho 67	167.26 Er 68	168.93 Tm 69	173.04 Yb 70	1 .97 Lu 71
† Actinide metals	227 Ac 89	232.04 Th 90	231 Pa 91	238.03 U 92	(237) Np 93	(242) Pu 94	(243) Am 95	(245) Cm 96	(249) Bk 97	(249) Cf 98	(253) E 99	(255) Fm 100	(256) Mv 101	(253) No 102	(257) Lw 103

Study Guide

22.1 Soddy's proposal of isotopes meant that not all atoms of the same element are identical. Explain why this proposal does not require that the atoms of a given element show differences in chemical behavior. Isotopes of an element have the same Z

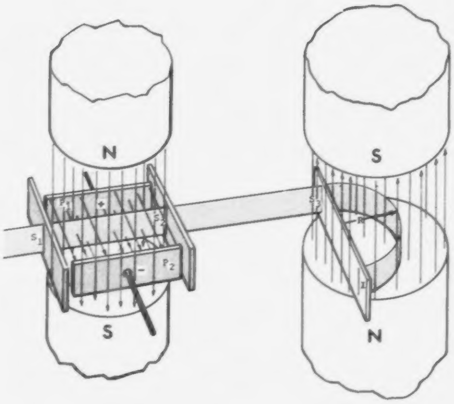
22.2 After Soddy's proposal of isotopes, how could one go about determining whether an apparently new element was really new and should be given a separate place in the periodic table, or was simply an isotope of an already known element? Determine if its chemical properties are unique.

22.3 At the National Bureau of Standards, in 1932, a gallon of liquid hydrogen was slowly evaporated until only about 1 gram remained. This residue allowed the first experimental check on the existence of the "heavy" hydrogen isotope H^2.

a) With the help of the kinetic theory of matter, explain why the evaporation should leave a residue with an increased concentration of the isotope of greater atomic mass. The lighter particles would diffuse away from the liquid surface more rapidly after evaporation, hence fewer of them would re-enter the liquid.

b) Why should the evaporation method be especially effective with hydrogen? The hydrogen isotopes have the largest ratio of isotopic masses (2:1) and hence the largest ratio of speeds ($1:\sqrt{2}$).

22.4 A mass spectrograph similar to that shown in the margin causes singly charged ions of chlorine 37 to travel a semi-circular path 1.000 meter in diameter and then strike a photographic plate.



a) How far apart will the traces of Cl^{37} and Cl^{35} be on the photographic plate? 0.054 m

b) What would be the diameter of the orbit of lead 208 ions if the same electric and magnetic field intensities were used to analyze a sample of lead? 5.64 m

c) The problems of maintaining a uniform magnetic field over surfaces larger than 1 square meter are considerable. What separation between lead 207 and lead 208 would be achieved if the diameter of the orbit of lead 208 were held to 1.000 meter? 0.005 m

22.5 Supply the missing data in these transformation equations:

a) ${}_{?}Pb^{212} \rightarrow {}_{?}Bi^{212} + ?$; ${}_{82}Pb^{212} \longrightarrow {}_{83}Bi^{212} + {}_{-1}e^{0}$

b) ${}_{?}Bi^{212} \rightarrow ? + {}_{-1}e^{0}$; ${}_{83}Bi^{212} \longrightarrow {}_{84}Po^{212} + {}_{-1}e^{0}$

c) $? \rightarrow {}_{?}Pb^{208} + {}_{2}He^{4}$. ${}_{84}Po^{212} \longrightarrow {}_{82}Pb^{201} + {}_{2}He^{4}$

22.6 The radioactive series originally called the actinium series is now known to start with the uranium isotope ${}_{92}U^{235}$. This parent member undergoes transmutations by emitting in succession the following particles: α, β, α, β, α, α, α, α, β, α, β. This last disintegration yields ${}_{82}Pb^{207}$, which is stable. From this information, and by consulting the periodic table, determine the complete symbol for each member of the series. List the members of the series in a column and beside each member give its mode of decay (similar to what was done in Table 21.1). chart, the end product being ${}_{82}Pb^{207}$.

22.7 In the following diagram of the thorium series, which begins with ${}_{90}Th^{232}$, the symbols used are those that were originally assigned to the members of the sequence:

$${}_{90}Th^{232} \xrightarrow{\alpha} {}_{?}MsTh_1^{?} \xrightarrow{?} {}_{89}MsTh_2^{?} \xrightarrow{\beta} {}_{?}RaTh^{?} \xrightarrow{\alpha} {}_{?}ThX^{?} \xrightarrow{?}$$

$$Tn^{?} \xrightarrow{?} {}_{84}ThA^{?} \xrightarrow{?} {}_{?}ThB^{?} \xrightarrow{\beta} {}_{?}ThC^{?} \xrightarrow{?} {}_{84}ThC'^{?} \xrightarrow{?}$$

ThD^{208} (stable)

Supply the missing data, then by consulting the periodic table replace the old symbols with the present ones. Indicate where alternative possibilities exist in the series. diagram, ending with ${}_{82}Pb^{208}$.

The alternatives are in the mode of decay of ${}_{84}Po^{216}$ and ${}_{83}Bi^{216}$.

22.8 From $_{94}Pu^{241}$, an isotope of plutonium produced artificially by bombarding uranium in a nuclear reactor, a radioactive series has been traced for which the first seven members are $_{94}Pu^{241}$, $_{95}Am^{241}$, $_{93}Np^{237}$, $_{91}Pa^{233}$, $_{92}U^{233}$, $_{90}Th^{229}$ and $_{88}Ra^{225}$. Outline the disintegration series for these first seven members, showing the modes of decay as in the preceding question. decay diagram, the modes of decay are β, α, α, β, α, α.

22.9 A trace of radioactivity in natural carbon makes it possible to estimate the age of materials which were once living. The radioactivity of the carbon is due to the presence of a small amount of the unstable isotope, carbon 14. This isotope is created mainly in the upper atmosphere by transformation (induced by cosmic rays) of the stable isotope carbon 13 to carbon 14. The rate of production of carbon 14 from carbon 13 matches the rate of beta-decay of carbon 14 into nitrogen 14, so the percentage of total carbon in the atmosphere consisting of carbon 14 is relatively constant. When carbon dioxide is used by plants in photosynthesis, the resulting cell growth incorporates the isotopes of carbon in the same proportions as exist in the atmosphere. The activity of the carbon at that time is 15.3 beta emissions per minute per gram of carbon. When the interaction with the atmosphere stops, for example, when a branch is broken off a living tree for use as a tool, its radioactivity begins to decrease at a rate characteristic of carbon 14. If the activity is measured at some later time, and if the half-life of carbon 14 is known, then one can use the decay curve given on page 24 to determine the time elapsed since the branch was taken from the tree. For example, suppose the activity dropped from 15.3 to 9.2 beta emissions per minute per gram of carbon. Knowing that the half-life of carbon is 5760 years, determine the time elapsed. 4000 years.

Repeat the procedure to calculate the age of charcoal from an ancient Indian fire pit if the activity of the carbon in the charcoal is found to be 1.0 beta emissions per minute per gram of carbon. What assumption are you making in this part of the problem? 25000 years

22.10 a) Find the average atomic mass of carbon by calculating the "weighted average" of the atomic masses of the two carbon isotopes. (Use the data of Table 22.1.) 12.011 amu

b) Find the average atomic mass of lithium. 6.941 amu

c) Find the average atomic mass of lead. 207.2 amu

22.11 The mass of a neutral helium is 4.00260 amu, and that of an electron is 0.00055 amu. From these data find the mass of the α particle in amu. 4.0015 amu

Chapter 23 Probing the Nucleus

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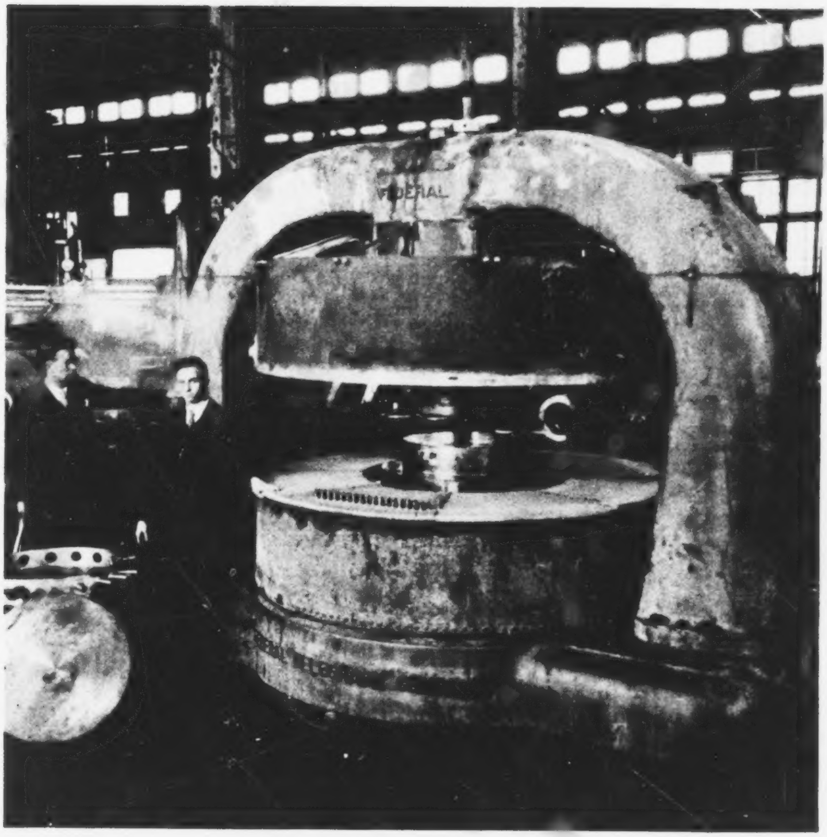


Ernest O. Lawrence (left) and M.S. Livingston (right) are shown standing beside the magnet for one of the earliest cyclotrons. Lawrence and Livingston invented the cyclotron in 1931, thereby initiating the development of high-energy physics in the United States.

23.1 The problem of the composition and structure of the atomic nucleus. The discoveries of radioactivity and isotopes raised new questions about the structure of atoms—questions which involved the atomic nucleus. We saw in Sec. 22.2 that the transformation rules of radioactivity could be described in terms of the Rutherford-Bohr model of the atom. But that model said nothing about the nucleus other than that it has a charge and mass, and that, when radioactive, it emits an α or a β particle. This implies that the nucleus has a composition or structure which changes when a radioactive process occurs. The question arose: how can we develop a theory or model of the atomic nucleus that will explain the facts of radioactivity and the existence of isotopes?

Summary 23.1
The discoveries of radioactivity and isotopes made clear the need for a model or theory to answer the question: what makes up the nucleus and how are the constituent particles put together?

The answer to this question makes up much of what is called nuclear physics. The problem of nuclear structure can be broken into two questions: (1) what are the building blocks of which the nucleus is made, and (2) how are the nuclear building blocks put together? Answers to the first question are considered in this chapter. In the next chapter we shall take up the question of how the nucleus is bound together. The attempt to solve the problem of nuclear structure, although not yet completely successful, has led not only to many new discoveries and to large-scale practical applications, but also to important social and political problems. Indeed, it has had consequences that have stretched far beyond physics and have had a serious impact on society in general. Some of these consequences will be discussed in Chapter 24.

23.2 The proton-electron hypothesis of nuclear structure. The emission of α and β particles by atoms of radioactive nuclides suggested that a model of the nucleus might be constructed by starting with these particles as building blocks. Such a model might be expected to be useful for the radioactive elements, because it would make it easy to see, for example, how a number of α particles could be emitted, in succession, in a radioactive series. But not all nuclei have masses that are multiples of the α-particle mass. Moreover, the nucleus of an atom of the lightest element, hydrogen, with an atomic mass of one unit (two units in the case of the heavy isotope), is too light to contain an α particle. So is the light isotope of helium, ${}_2\mathrm{He}^3$.

Summary 23.2
1. The proton, the nucleus of the hydrogen atom in the Rutherford-Bohr model of atomic structure, must play an important part in any nuclear model.

2. A proton-electron hypothesis, although attractive in some respects, had to be ruled out; an electron just cannot exist inside the nucleus.

SG 23.1

A positively charged particle with a mass of one unit would be more satisfactory as a nuclear building block. Such a particle does indeed exist: the nucleus of the common isotope of hydrogen. This particle has been named the proton. According to the Rutherford-Bohr theory of atomic structure, the hydrogen atom consists of a proton with a single electron revolving around it.

Proton—from the Greek "protos" (first). It is not known who suggested the name originally—it is found in the literature as far back as 1908. In 1920 Rutherford's formal proposal of the name proton was accepted by the British Association for the Advancement of Science.

In the preceding chapter (Sec. 22.4), we discussed Aston's whole-number rule, expressing the experimental result that the atomic masses of the nuclides are very close to integers. This rule, together with the properties of the proton—its mass of very nearly one unit and its single positive charge—made it appear possible that all atomic nuclei are made up of protons. Could a nucleus of mass number A consist of A protons? If this were the case, the charge of the nucleus would be A units; but, except for hydrogen, the nuclear charge Z is always less than A—usually less than ½A. To get around this difficulty, it was assumed that in addition to the protons, atomic nuclei contain just enough electrons to cancel the charge of the extra protons, that is, A-Z electrons. These electrons would contribute only a small amount to the mass of the nucleus, but would make the net charge equal to +Z units as required. It was thus possible to consider the atom as consisting of a nucleus of A protons and A-Z electrons, with Z additional electrons outside the nucleus to make the entire atom electrically neutral. For example, an atom of $_8O^{16}$ would have a nucleus with 16 protons and 8 electrons, with 8 additional electrons outside the nucleus. This model of the nucleus is known as the proton-electron hypothesis of nuclear composition. SG 23.2

The proton-electron hypothesis seemed to be consistent with the emission of α and β particles by atoms of radioactive substances. Since it was assumed that the nucleus contained electrons, explanation of beta decay was no problem: when the nucleus is in an appropriate state it may simply eject one of its electrons. It also seemed reasonable that an α particle could be formed, in the nucleus, by the combination of four protons and two electrons; an α particle might exist as such, or it might be formed at the instant of emission.

The proton-electron hypothesis is similar to an earlier idea suggested by English physician William Prout in 1815. On the basis of the small number of atomic masses then known, he proposed that all atomic masses are whole numbers, that they might be integral multiples of the atomic mass of hydrogen and that all the elements might be built up of hydrogen. Prout's hypothesis was discarded when, later in the nineteenth century, the atomic masses of some elements were found to be fractional, in particular, those of chlorine (35.46 units) and copper (63.54 units). With the discovery of isotopes, it was found that the fractional atomic masses of chlorine and copper, like that of neon, are those of mixtures of isotopes, but each separate isotope has an atomic mass very close to an integer.

Although the proton-electron hypothesis was satisfactory in some respects—as in accounting for nearly integral (whole number) isotopic masses and in being consistent with the emission of α and β particles by radioactive nuclides—it led to serious difficulties and had to be given up. The existence of electrons inside the nucleus had to be ruled out for a number of reasons too complicated to discuss at this point.

Q1 Why was the idea of hydrogen atoms being a basic building block of all atoms given up in the nineteenth century?

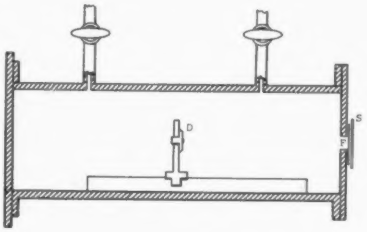
Q2 On the basis of the proton-electron hypothesis, what would a nucleus of ${}_6C^{12}$ contain?

Summary 23.3

1. In 1919 Rutherford detected artificially induced transmutations when bombarding nitrogen atoms with alpha particles.

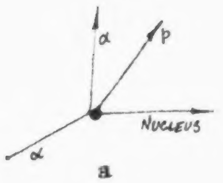
2. Nuclear reactions of this type eventually led to the discovery of the neutron.

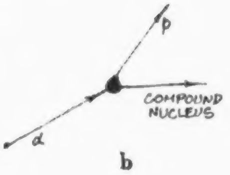
23.3 The discovery of artificial transmutation. A path which led to a better understanding of nuclear composition was opened in 1919. In that year Rutherford found that when nitrogen gas was bombarded with α particles from bismuth 214, swift particles were produced which could travel farther in the gas than did the α particles themselves. When these particles struck a scintillation screen, they produced flashes of light of the same intensity as would be produced by positive hydrogen ions (protons). Measurements of the effect of a magnetic field on the paths of the particles suggested that they were indeed protons. Rutherford ruled out, by means of careful experiments, the possibility that the protons came from hydrogen present as an impurity in the nitrogen. Since the nitrogen atoms in the gas were the only possible source of protons, Rutherford concluded that an α particle, in colliding with a nitrogen nucleus, can occasionally knock a small particle—a proton—out of the nitrogen nucleus. In other words, Rutherford deduced that an α particle can cause the artificial disintegration of a nitrogen nucleus, with one of the products of the disintegration being a proton. The experimental results showed that only one proton was produced for about one million α particles passing through the gas. Between 1921 and 1924, Rutherford and Chadwick extended the work on nitrogen to other elements and found evidence for the artificial disintegration of all the light elements from boron to potassium, with the exception of carbon and oxygen.



Rutherford's diagram of the apparatus used to detect the protons from disintegrations produced by α particles. The α source was on a movable stand. Nitrogen nuclei in the nitrogen gas which filled the box are transmuted by the α's. At the end of the box was a piece of silver foil thick enough to stop α's, but not protons. Behind the foil was a lead sulfide screen which would show flashes of light when struck by protons. (The photo on p. 73 of the Unit 5 Text shows Rutherford holding this apparatus.)

The next step was to determine the nature of the nuclear process leading to the emission of the proton. Two hypotheses were suggested for this process: (a) the nucleus of the





bombarded atom promptly loses a proton "chipped off" as the result of a collision with a swift α particle; or (b) the α particle is captured by the nucleus of the atom it hits forming a new nucleus which, a moment later, emits a proton. It was possible to distinguish experimentally between these two possible cases by using a device, called a "cloud chamber," which reveals the path or track of an individual charged particle. The cloud chamber was invented in 1912 by C. T. R. Wilson; a schematic diagram of the instrument is shown in Fig. 23.1. In case (a) four tracks should be seen in a photograph of a disintegration event: the track of the α particle before the collision, the track of the α particle after collision and the tracks of the proton and recoiling nucleus after collision. In case (b) the α particle should disappear in the collision, and only three tracks would be seen: that of the α particle before the collision and the tracks of the proton and recoil nucleus after the collision. The choice between the two possibilities was settled in 1925 when P. M. S. Blackett studied the tracks produced when α particles passed through nitrogen gas in a cloud chamber. He found, as shown in Fig. 23.2, that the only tracks which could be seen were those of the incident α particle, a proton and the recoil nucleus. The absence of a track corresponding to the presence of an α particle after the collision proved that the α particle disappeared completely and that case (b) is the correct interpretation.

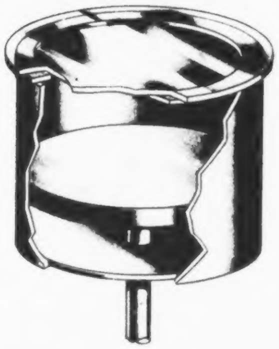


Fig. 23.1 The Wilson cloud chamber. When the piston is moved down rapidly the gas in the cylinder becomes supersaturated with water vapor. The water vapor will condense on the ions created along the path of a high-energy charged particle, thereby making the track.

For his invention of the cloud chamber Charles Thomson Rees Wilson (1869-1959) of Scotland shared the 1927 Nobel Prize in physics with Arthur H. Compton.

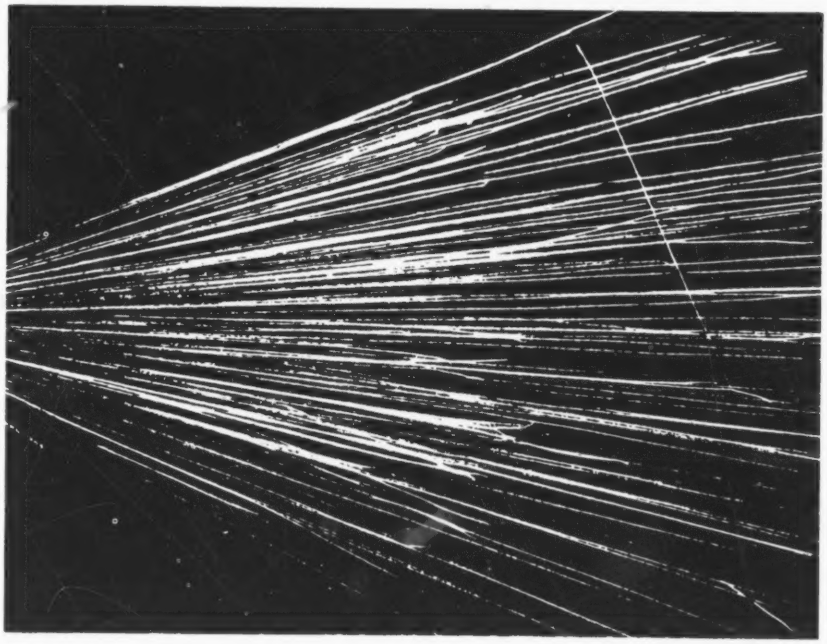
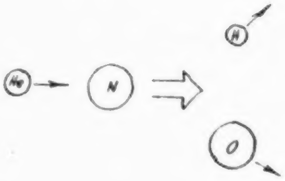


Fig. 23.2 α-particle tracks in a cloud chamber filled with nitrogen gas. At the right, one α particle has hit a nitrogen nucleus; a proton is ejected upward toward the left, and the resulting oxygen nucleus recoils downward to the right. (From P. M. S. Blackett, 1925)

The process in which an α particle is absorbed by a nitrogen nucleus and a proton is emitted may be represented by an equation which is analogous to the equations used near the end of Sec. 22.6 to represent radioactive decay. The equation expresses the fact that the total mass number is the same before and after the collision (conservation of mass number) and the fact that the total charge is the same before and after the collision (conservation of charge). The atomic number, the mass number and the nuclear charge are known for the target nucleus ${}_7\text{N}^{14}$, the incident α particle ${}_2\text{He}^4$ and the proton ${}_1\text{H}^1$. The product nucleus will therefore have the atomic number $7 + 2 - 1 = 8$, and the mass number $14 + 4 - 1 = 17$. The product nucleus is ${}_8\text{O}^{17}$, an isotope of oxygen, and the disintegration process may be represented by the nuclear reaction:

See "The Tracks of Nuclear Particles" in Project Physics Reader 6.

$$ {}_2\text{He}^4 + {}_7\text{N}^{14} \longrightarrow {}_8\text{O}^{17} + {}_1\text{H}^1 . $$



This reaction shows that a transmutation of an atom of one chemical element into an atom of another chemical element has taken place. This transmutation did not occur spontaneously, as is the case in natural radioactivity, but was man-made; it was produced by bombarding target atoms (nuclei) with projectiles from a radioactive nuclide. In the paper in which he reported this first artificially produced nuclear reaction, Rutherford said,

SG 23.3

> The results as a whole suggest that, if α particles—or similar projectiles—of still greater energy were available for experiment, we might expect to break down the nuclear structure of many of the lighter atoms.

The further study of reactions involving light nuclei led (as we shall see in the next section) to the discovery of a new particle—the neutron—and to a better theory of the constitution of the nucleus. Many types of reactions have been observed with nuclei of all masses, from the lightest to the heaviest, and the possibilities indicated by Rutherford have been realized to an extent far beyond what he could have imagined in 1919.

Q3 What evidence showed that the bombarding α particle was absorbed by the nitrogen nucleus, rather than bounced off?

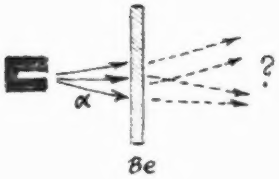
23.4 The discovery of the neutron. It was suggested by Rutherford in 1920 that an electron and a proton inside the nucleus might be tied to each other so closely as to form a neutral particle. Rutherford even suggested the name "neutron" for this particle. Physicists looked for neutrons, but the search presented at least two difficulties: (1) there were no naturally occurring sources of neutrons; and (2) the methods used for detecting

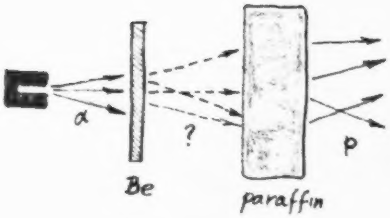
Summary 23.4
1. Convincing evidence for the existence of neutrons was found in 1932, in the form of uncharged rays.

2. Using conservation of momentum and energy relations, Chadwick calculated the mass of the neutron from data on neutron collisions with different nuclei.

atomic particles all depended on effects of the electric charge of the particles and could not be applied directly to neutral particles. Until 1932, the search for neutrons was unsuccessful.

The proof of the existence of neutrons by the English physicist, James Chadwick, came in 1932 as the result of a series of experiments on nuclear reactions made by physicists in different countries. The discovery of the neutron is a good example of how physicists operate—how they think about problems and arrive at solutions; it is an excellent "case history" in experimental science. Working in Germany in 1930, W. G. Bothe and H. Becker found that when samples of boron and beryllium were bombarded with α particles, they emitted radiations which appeared to be of the γ-ray type, that is, which had no electric charge. Beryllium gave a particularly marked effect of this kind. Observations by physicists in Germany, France and Great Britain showed that the radiation from the beryllium penetrated further (in lead, for example) than any γ radiation found up to that time and had an energy of about 10 MeV. The radiation was thus much more energetic than the γ rays previously observed, and, as a result, aroused much interest. Among those who investigated this radiation were the French physicists Frédéric Joliot and his wife Irène Curie, a daughter of the discoverers of radium; they studied the absorption of the radiation in paraffin, a material rich in hydrogen. They found in the course of their experiments that the radiation from beryllium, when it fell on paraffin, ejected large numbers of protons from the paraffin. The energies of these protons were found to be about 5 MeV. Using the principles of conservation of momentum and energy, they calculated the energy a γ ray would need if it were to transfer 5 MeV to a proton in a collision. The result was about 50 MeV, a value much greater than the 10 MeV that had been measured. In addition, the number of protons produced was found to be much greater than that predicted on the assumption that the radiation consisted of γ rays, that is, photons or quanta of radiation.





James Chadwick (born 1891) received the Nobel Prize in Physics in 1935 for his discovery of the neutron.

These discrepancies (between the results of two sets of experiments and between theory and experiment) left physicists in a dilemma. Either they could give up the application of conservation of momentum and energy to the collisions between the radiation and the protons in the paraffin, or they could adopt another hypothesis about the nature of the radiation. Now, if there is any one thing physicists do not want to do it is to give up the principles of conservation of momentum and energy. These principles are so basic to scientific thought and have proven so useful that physicists tried very hard to find an alternative to giving them up.

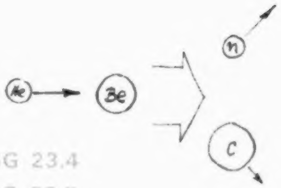
See "Conservation Laws" in Project Physics Reader 6.

In 1932, Chadwick found a successful alternative, a new hypothesis about the nature of the radiation. In his paper "The Existence of a Neutron," he said:

> If we suppose that the radiation is not a quantum radiation, but consists of particles of mass very nearly equal to that of the proton, all the difficulties connected with the collisions disappear, both with regard to their frequency and to the energy transfers to different masses. In order to explain the great penetrating power of the radiation, we must further assume that the particle has no net charge. We must suppose it to consist of a proton and electron in close combination, the 'neutron' discussed by Rutherford in his Bakerian Lecture of 1920.

According to Chadwick's hypothesis, when a light element (such as beryllium) is bombarded with α particles, a second kind of nuclear reaction can take place (in addition to the one that produces protons):

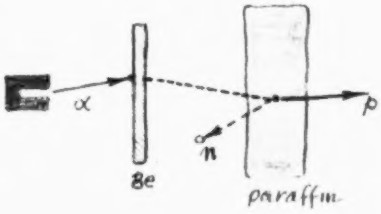
$$_2\mathrm{He}^4 + {}_4\mathrm{Be}^9 \longrightarrow {}_6\mathrm{C}^{12} + {}_0\mathrm{n}^1.$$



The symbol $_0n^1$ represents the neutron postulated by Chadwick, with zero charge and mass number equal to 1.

SG 23.4
SG 23.5

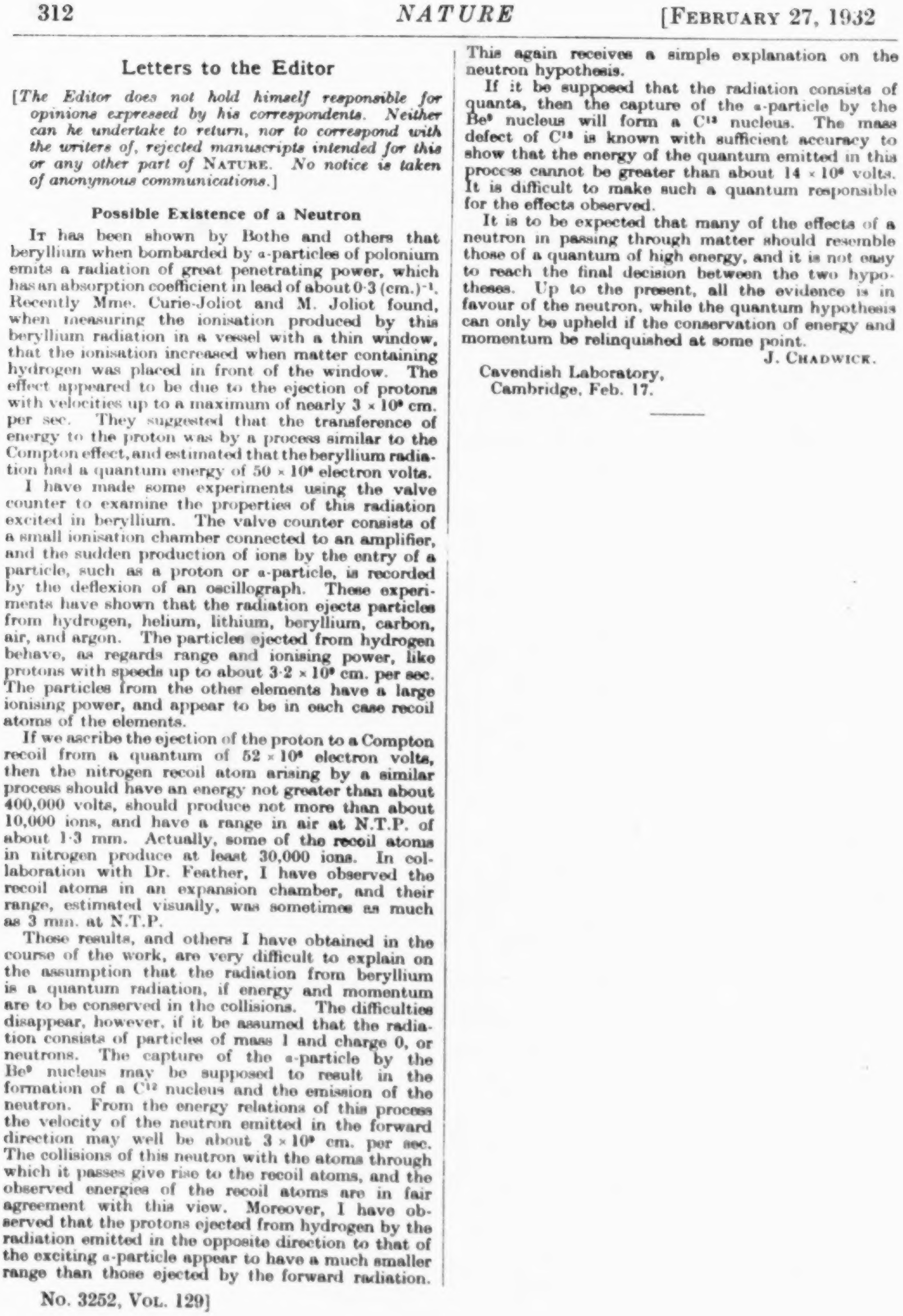
The neutrons postulated by Chadwick had no charge, and could even penetrate bricks of a material as dense as lead without giving up their energy. Neutrons could also approach charged nuclei without being repelled or deflected by strong electrostatic forces, as α particles are deflected when scattered by nuclei. In a head-on collision with a hydrogen nucleus (proton), whose mass should be very close to that of the neutron, the neutron could give up practically all its kinetic energy to the proton. The latter could then be observed because of the ionization it produces, and its kinetic energy could be determined. Thus Chadwick's hypothesis could account in a qualitative way for the observed effects of the "radiation" from beryllium.



It was still necessary, however, to determine the mass of the neutron quantitatively, and this Chadwick did by means of some additional experiments. His method was based on the fact that in a collision between a moving and a stationary particle, the speed imparted to the latter is greatest in a head-on collision, in which the stationary particle now moves off in the same direction as that in which the incident particle approached it. A formula for the maximum speed can be derived from the equations of conservation of energy and momentum in a head-on collision. See page 61

See "Some Personal Notes on the Search for the Neutron" in Project Physics Reader 6.

L49: Collisions with an unknown object



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Letters to the Editor

[*The Editor does not hold himself responsible for opinions expressed by his correspondents. Neither can he undertake to return, nor to correspond with the writers of, rejected manuscripts intended for this or any other part of* NATURE. *No notice is taken of anonymous communications.*]

Possible Existence of a Neutron

IT has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found, when measuring the ionisation produced by this beryllium radiation in a vessel with a thin window, that the ionisation increased when matter containing hydrogen was placed in front of the window. The effect appeared to be due to the ejection of protons with velocities up to a maximum of nearly 3×10^9 cm. per sec. They suggested that the transference of energy to the proton was by a process similar to the Compton effect, and estimated that the beryllium radiation had a quantum energy of 50×10^6 electron volts.

I have made some experiments using the valve counter to examine the properties of this radiation excited in beryllium. The valve counter consists of a small ionisation chamber connected to an amplifier, and the sudden production of ions by the entry of a particle, such as a proton or α-particle, is recorded by the deflexion of an oscillograph. These experiments have shown that the radiation ejects particles from hydrogen, helium, lithium, beryllium, carbon, air, and argon. The particles ejected from hydrogen behave, as regards range and ionising power, like protons with speeds up to about $3{\cdot}2 \times 10^9$ cm. per sec. The particles from the other elements have a large ionising power, and appear to be in each case recoil atoms of the elements.

If we ascribe the ejection of the proton to a Compton recoil from a quantum of 52×10^6 electron volts, then the nitrogen recoil atom arising by a similar process should have an energy not greater than about 400,000 volts, should produce not more than about 10,000 ions, and have a range in air at N.T.P. of about 1·3 mm. Actually, some of the recoil atoms in nitrogen produce at least 30,000 ions. In collaboration with Dr. Feather, I have observed the recoil atoms in an expansion chamber, and their range, estimated visually, was sometimes as much as 3 mm. at N.T.P.

These results, and others I have obtained in the course of the work, are very difficult to explain on the assumption that the radiation from beryllium is a quantum radiation, if energy and momentum are to be conserved in the collisions. The difficulties disappear, however, if it be assumed that the radiation consists of particles of mass 1 and charge 0, or neutrons. The capture of the α-particle by the Be^9 nucleus may be supposed to result in the formation of a C^{12} nucleus and the emission of the neutron. From the energy relations of this process the velocity of the neutron emitted in the forward direction may well be about 3×10^9 cm. per sec. The collisions of this neutron with the atoms through which it passes give rise to the recoil atoms, and the observed energies of the recoil atoms are in fair agreement with this view. Moreover, I have observed that the protons ejected from hydrogen by the radiation emitted in the opposite direction to that of the exciting α-particle appear to have a much smaller range than those ejected by the forward radiation. This again receives a simple explanation on the neutron hypothesis.

If it be supposed that the radiation consists of quanta, then the capture of the α-particle by the Be^9 nucleus will form a C^{13} nucleus. The mass defect of C^{13} is known with sufficient accuracy to show that the energy of the quantum emitted in this process cannot be greater than about 14×10^6 volts. It is difficult to make such a quantum responsible for the effects observed.

It is to be expected that many of the effects of a neutron in passing through matter should resemble those of a quantum of high energy, and it is not easy to reach the final decision between the two hypotheses. Up to the present, all the evidence is in favour of the neutron, while the quantum hypothesis can only be upheld if the conservation of energy and momentum be relinquished at some point.

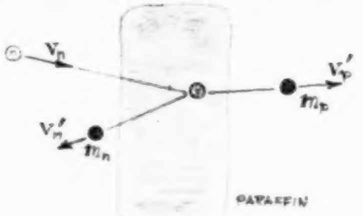
J. CHADWICK.

Cavendish Laboratory,
Cambridge, Feb. 17.

No. 3252, VOL. 129]

Chadwick's first published report of his neutron conjecture.

Determining the Neutron's Mass



The sketch above represents the perfectly elastic collision of a neutron and a proton. To determine the mass of the neutron, we proceed by considering a head-on collision: conservation of kinetic energy and conservation of momentum provide two algebraic equations which must both hold. Combining the equations algebraically (solving the momentum equation for v_n', substituting this for v_n' in the energy equation, expanding, collecting terms and solving for v_p') leads to an expression for v_p'. This expression includes the term v_n, however, which can't be measured. We can eliminate v_n from the equation by analyzing another collision and combining the results with what we already have.

CONSERVATION OF ENERGY

$$\frac{1}{2} m_n v_n^2 = \frac{1}{2} m_n v_n'^2 + \frac{1}{2} m_p v_p'^2$$

CONSERVATION OF MOMENTUM

$$m_n v_n = m_n v_n' + m_p v_p'$$

$$v_n' = \frac{m_n v_n - m_p v_p'}{m_n}$$

$$\frac{1}{2} m_n v_n^2 = \frac{1}{2} m_n \left(\frac{m_n v_n - m_p v_p'}{m_n}\right)^2 + \frac{1}{2} m_p v_p'^2$$

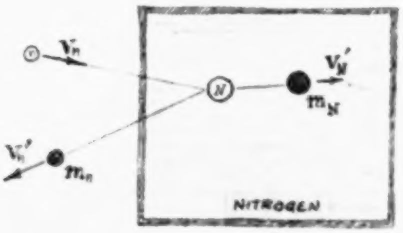
$$m_n v_n^2 = \frac{m_n^2 v_n^2 - 2 m_n m_p v_n v_p' + m_p^2 v_p'^2}{m_n} + m_p v_p'^2$$

$$m_n^2 v_n^2 = m_n^2 v_n^2 - 2 m_n m_p v_n v_p' + m_p^2 v_p'^2 + m_n m_p v_p'^2$$

$$m_p^2 v_p'^2 + m_n m_p v_p'^2 = 2 m_n m_p v_n v_p'$$

$$m_p v_p' + m_n v_p' = 2 m_n v_n$$

$$v_p' = \frac{2 m_n v_n}{m_p + m_n}$$



The sketch above represents a perfectly elastic collision between a neutron and a nitrogen nucleus. When the collision is head-on, we can write energy and momentum equations similar to what we wrote before, but this time leading to an expression for v_N'. This expression also includes the unmeasurable v_n.

The v_p' equation and v_N' equation are then combined algebraically (eliminating the v_n) and solved for m_n. The expression for m_n now contains only terms which can be measured—so m_n can be calculated.

CONSERVATION OF ENERGY

$$\frac{1}{2} m_n v_n^2 = \frac{1}{2} m_n v_n'^2 + \frac{1}{2} m_N v_N'^2$$

CONSERVATION OF MOMENTUM

$$m_n v_n = m_n v_n' + m_N v_N'$$

$$v_N' = \frac{2 m_n v_n}{m_N + m_n}$$

$$\frac{v_p'}{v_N'} = \frac{m_N + m_n}{m_p + m_n}$$

$$m_n = \frac{m_N v_N - m_p v_p}{v_p - v_N}$$

SG 23.5
SG 23.6

Chadwick calculated the mass of the neutron to be 1.16 amu. The difficulties of measuring the speeds of recoil H^1 and N^{14} kept this from being a very precise value, but it was good enough to show that the neutron has a mass close to that of the proton; thus Chadwick's hypothesis did indeed offer a satisfactory solution to the problem of the "radiation" emitted when boron and beryllium were bombarded with α particles. In more precise experiments, Chadwick found that the neutron mass is between 1.005 and 1.008 amu. The best methods now available for determining the neutron mass give 1.008665 amu as compared with the proton mass of 1.007276 amu (based on the scale C^{12} = 12.000 000).

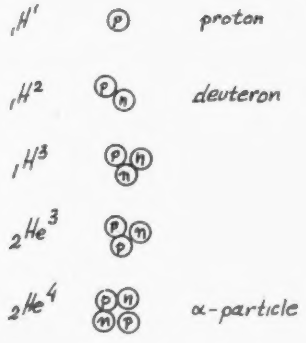
Much research has been done since 1932 on the properties of neutrons and on the interactions between neutrons and atoms. A branch of study called neutron physics has been developed. Neutron physics deals with the production of neutrons, their detection and their interaction with atomic nuclei and with matter in bulk. This research has led, among other things, to the discovery of nuclear fission, to be discussed in Chapter 24.

Q4 Why wasn't the penetrating radiation from bombarded beryllium interpreted as being γ rays?

Q5 Why did the mass of a neutron have to be investigated by measurements on protons?

Summary 23.5
1. With the discovery of the neutron, the proton-neutron theory of the composition of nuclei was established:
(a) the atomic number Z corresponds to the number of protons inside the nucleus, (b) the mass number A gives the total number of particles, and (c) the difference (A-Z) represents the number of neutrons.

2. β decay occurs when a neutron is transformed into an electron, proton and a third particle.



23.5 The proton-neutron theory of the composition of atomic nuclei.

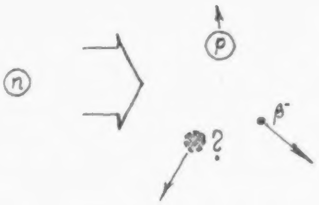
The discovery of the neutron, with an atomic mass close to one unit and with no electric charge, confirmed Rutherford's suggestion that the atomic nucleus is made up of protons and neutrons. This hypothesis was soon used as the basis of a detailed theory of the nucleus by Heisenberg in 1932, and is still the basis of attempts to describe the properties and structure of the nucleus. According to the proton-neutron hypothesis, the nucleus of atomic number Z and mass number A consists of Z protons and A-Z neutrons. The nuclei of the isotopes of a given element differ only in the number of neutrons they contain. Thus the nucleus of the hydrogen isotope of mass number 1 contains one proton; the nucleus of deuterium (hydrogen isotope of mass number 2) contains one proton and one neutron. The nucleus of the neon isotope Ne^{20} contains 10 protons and 10 neutrons; while that of Ne^{22} contains 10 protons and 12 neutrons. The atomic number Z, identified with the change in the nucleus, is the number of protons it contains. The mass number A is the total number of protons and neutrons. If we use the term nucleons to refer to both kinds of nuclear particles, then A is the number of nucleons.

SG 23.8
SG 23.9

The proton-neutron hypothesis can be shown to be consistent with the facts of radioactivity. If two protons and two neutrons could combine, the resulting particle would have Z=2 and A=4—just the properties of the α particle. The emission of the combination of two protons and two neutrons (in the form of an α particle) would be consistent with the first transformation rule of radioactivity. (The α particle might exist as such in the nucleus, or it might be formed at the instant of emission; the latter possibility is now considered more likely.) But, if the nucleus consists of protons and neutrons, where could a β particle come from? This question is more difficult to answer than that of the origin of an α particle. The second transformation rule of radioactivity provides a clue: when a nucleus emits a β particle its charge Z increases by one unit while its mass number A remains unchanged. This would happen if a neutron were to change into a proton and a β particle.

See "Models of the Nucleus" in Project Physics Reader 6.

We now know that a free neutron—a neutron separated from an atom—changes into a proton, an electron and another, uncharged particle (which we shall discuss later). The disintegration of the neutron is a transformation into three particles, not just the separation of a neutron into a proton and an electron. The half-life of free neutrons is about 12 minutes. In the β decay of a radioactive nucleus (since β particles are not present in the nucleus) a β particle must be created in the act of β decay. This can occur if a neutron in the nucleus is transformed into a proton, an electron (and the not-yet discussed neutral particle). This concept forms the basis of the currently accepted theory of β decay, a theory which has successfully accounted for all the known phenomena of β decay.



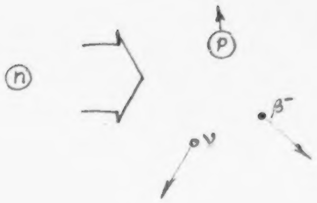
Q6 According to the proton-neutron theory of the nucleus, what is in the nucleus of ${}_{7}N^{14}$?

Q7 Describe a helium atom in terms of the three elementary particles: proton, neutron and electron.

Q8 If nuclei do not contain β particles, how can β emission be explained?

Summary 23.6
The principles of conservation of energy and momentum appeared to be violated in β decay; the neutrino was postulated to be responsible for the apparent discrepancy. In 1959 neutrinos were detected. We now know of several kinds of neutrinos.

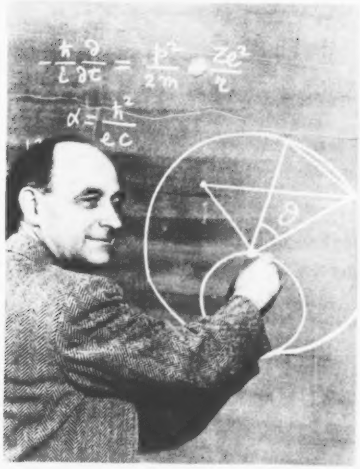
23.6 The neutrino. The description of β decay in terms of the transformation of a neutron in the nucleus involves one of the most fascinating stories in modern physics: the prediction and eventual discovery of the particles known as the neutrino and the antineutrino. Quantitative studies of the energy relations in β decay during the 1920's and 1930's raised a difficult and serious question. Methods were devised for determining the energy change in a nucleus



during β decay. According to the principle of conservation of energy, the energy lost by the nucleus should be equal to the energy carried off by the β particle. But, when the energy lost by the nucleus was compared with the measured kinetic energy of the β particle, the latter was nearly always smaller: some of the energy lost by the nucleus seemed to have disappeared. Measurements made on a large number of β - emitters indicated that about two-thirds of the energy lost by the β-decaying nuclei seemed to disappear. Attempts to find the missing energy failed. For example, some physicists thought that the missing energy might be carried off by γ rays; but no such γ rays could be detected experimentally. The principle of conservation of energy seemed to be violated in β decay. Similar discrepancies were found in measurements of the momentum of the electron and the recoiling nucleus.

As in the case of the experiments that led to the discovery of the neutron, physicists tried very hard to find an alternative to accepting the failure of the principles of conservation of energy and momentum. An Austrian physicist, Wolfgang Pauli, Jr., suggested in 1933 that another particle is emitted in β decay along with the electron, and that this particle carries off the missing energy and momentum. This hypothetical particle would have no electric charge because the positive charge of the proton and the negative charge of the electron together are equal to the zero charge of the neutron. (Conservation of electric charge!) The mass-energy balance in the decay of the neutron indicated that the mass of the hypothetical particle should be very small—much smaller than the mass of an electron, and possibly even zero. The combination of zero electric charge and zero or nearly zero mass would make the particle extremely hard to find.

The Italian physicist Enrico Fermi called the suggested particle the "neutrino" or "little neutron." In 1934 Fermi constructed a theory of β decay based on Pauli's suggestion. This theory has been successful, as mentioned earlier, in describing all the known facts of β decay. From 1934 on, the neutrino was accepted as a "real" particle for two reasons, both theoretical: it saved the principle of conservation of energy in β decay, and it could be used successfully both to describe the results of experiments in β decay and to predict the results of new experiments. Many unsuccessful attempts were made to detect neutrinos over a period of 25 years. Finally, in 1959, neutrinos were detected in an experiment using the extremely large flow of neutrinos that comes out of a nuclear reactor (see Chapter 24). The detection of neutrinos involves detecting the products of a reaction



Enrico Fermi, one of the most productive physicists of this century.

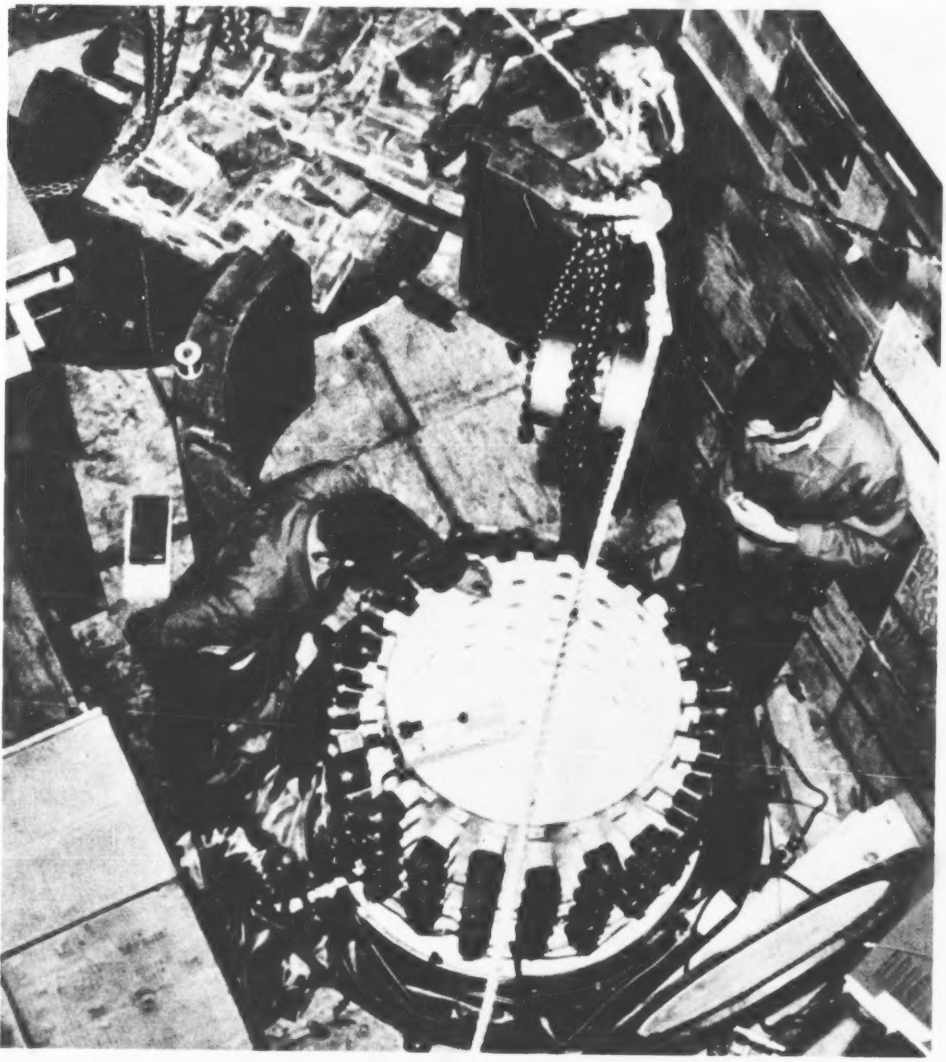
provoked by a neutrino. The reaction used was reverse β decay—the production of a proton from a neutron. Again the faith of physicists in the principle of conservation of energy was justified.

There is still one more complication: it is now known that there are several kinds of neutrinos. The one involved in β decay (as discussed so far) is referred to as an antineutrino, and is denoted by the symbol $\bar{\nu}$ (Greek letter "nu," with a bar over it). The transformation of a neutron is then written:

See Appendix B, page 119.

$$ {}_{1}n^{0} \longrightarrow {}_{1}p^{1} + {}_{-1}e^{0} + \bar{\nu} $$

Q9 Why was an unknown, almost undetectable particle invented to patch up the theory of β decay?



The first detection of neutrinos was in this tank. Reactions provoked by neutrinos cause flashes of light in the liquid with which the tank is filled. The flashes are detected by the photoelectric tubes which stud the tank wall.

F52: The linear accelerator

Summary 23.7

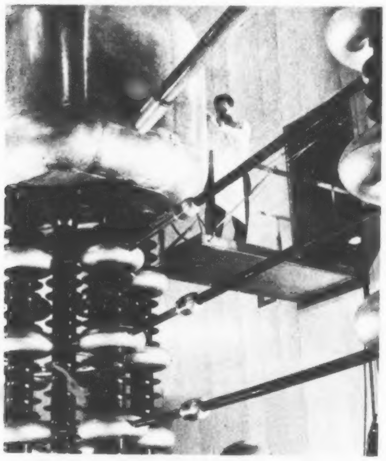
1. Until 1932 all artificial nuclear reactions were induced by α particles from natural radioactive sources.

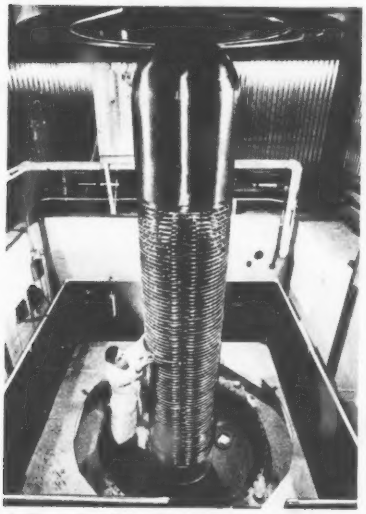
2. To learn more about the nucleus, projectile particles of much higher energy were required.

23.7 The need for particle accelerators. Up to 1932 the study of nuclear reactions was limited by the kind of projectile that could be used to bombard nuclei: only α particles from the naturally radioactive nuclides could bring about reactions. Progress was limited because α particles could be obtained only in beams of low intensity and with energies less than 8 MeV. These relatively low-energy particles could produce transmutations only in light elements. When heavier elements are bombarded with α particles, the repulsive electric force exerted by the greater charge of the heavy nucleus on an α particle makes it difficult for the α particle to reach the nucleus. The probability of a nuclear reaction taking place becomes very small—almost zero. But because the interest in nuclear reactions was great, physicists sought methods of increasing the energy of charged particles to be used as projectiles.

See "The Evolution of the Cyclotron" and "The Cyclotron as Seen by..." in Project Physics Reader 6.

There were advantages to be gained by using particles that have only one positive charge—particles such as the proton or the deuteron (the nucleus of the deuterium atom). Having but a single charge, these particles would experience smaller repulsive electric forces than would α particles in the neighborhood of a nucleus, and thus might succeed in producing transmutations of heavy target nuclei. Protons or deuterons could be obtained from positive-ray tubes, but their energies would not be high enough. Some device was needed to accelerate these charged particles to higher energies. Such devices might also offer other advantages: the speed (and energy) of the bombarding particles could be controlled by the experimenter; and very intense projectile beams might be obtained. It would be possible to find how the variety and abundance of nuclear reactions depend on the energy of the bombarding particles.


First stage of a 750 kilovolt proton accelerator (see p. 59 of Unit 4).


A Van de Graaff generator built on a vertical axis.

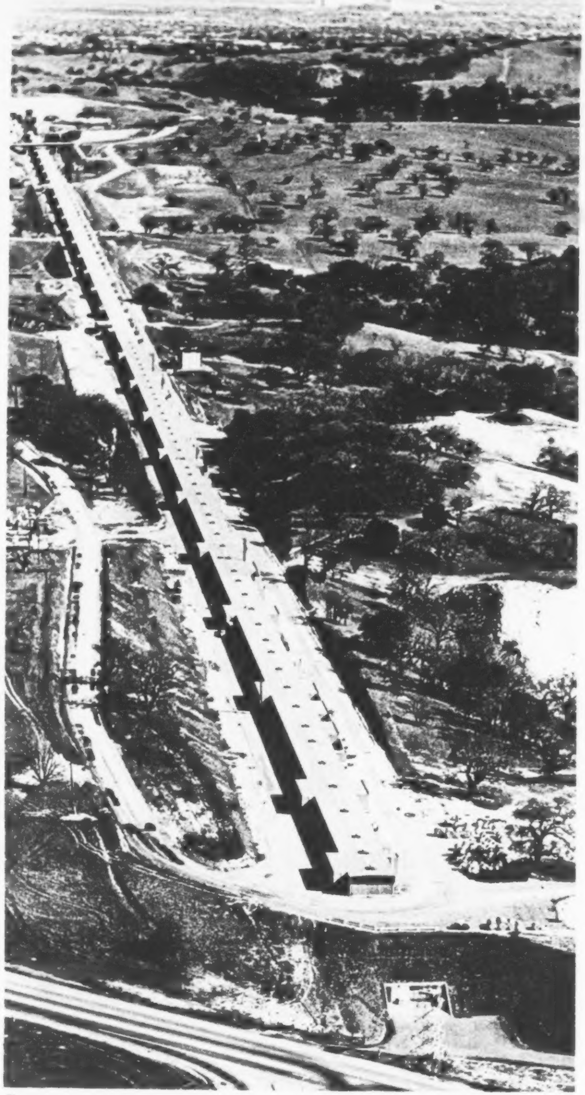
Since 1930 many devices for accelerating charged particles have been invented. In each case the particles (electrons, protons, deuterons, α particles or heavy ions) are accelerated by an electric field. In some cases a magnetic field is used to control the path of the particles, that is, to steer them. Accelerators have become basic tools for research in nuclear and high-energy physics. Also, they are used in the production of radioactive isotopes and serve as radiation sources for medical and industrial purposes. The table presented on the next page summarizes the major types of particle accelerators now being used.

Next on the long-range planning list of the U.S. Atomic Energy Commission is a 200 BeV particle accelerator to be

3. This need led to the development of machines using electric and magnetic fields to accelerate particles to high energies; the trend towards designing machines of higher and higher energy has not ended. 4. Even though many new particles have been discovered by means of accelerators, the problem of the detailed structure of the nucleus has not yet been solved.

Table 23.1 Major types of particle accelerators

Type	Principle of Operation	Maximum Energy	Particles	Notes
ONCE-THROUGH ACCELERATION				
Cockcroft-Walton	direct high voltage potential	≈4 MeV	various	commercially available
Van de Graaff generator	high voltage by moving belt	≈3 MeV ≈14 MeV	electrons protons	commercially available
Linear accelerator	successive application of high frequency voltages	≈10 MeV per particle	heavy ions	Lawrence Radiation Laboratory and Yale University
Linear accelerator	pulsed high frequency wave	≈20 BeV	electrons	Stanford University, two miles long
CYCLIC ACCELERATION				
Betatron	magnetic induction (electrons accelerated in an evacuated tube between the poles of an electromagnet)	≈300 MeV	electrons	Largest machine at the University of Illinois
Cyclotron	voltage of constant frequency applied to particles in fixed magnetic field	≈12 MeV ≈24 MeV ≈48 MeV	protons deuterons particles	numerous installations
Synchro-cyclotron	voltage of variable frequency applied to particles in fixed magnetic field	≈750 MeV	protons	184-inch unit at Lawrence Radiation Laboratory, Berkeley
Electron synchrotron	voltage of constant frequency applied to particles orbiting in variable magnetic field	≈7 BeV	electrons	Hamburg, Germany (7.5 BeV), Cambridge Electron Accelerator (6 BeV) operated by Harvard and M.I.T.
Proton synchrotron	synchronized voltage of high frequency applied to particles orbiting in variable magnetic field	≈12 BeV	protons	6.2 BeV "Bevatron" at Lawrence Radiation Laboratory, 3 BeV Cosmotron at Brookhaven, 3 BeV at Princeton, and 12.5 BeV synchrotron at Argonne National Laboratory
Alternating gradient synchrotron	same as synchrotron except successive segments of magnetic field have opposite curvature.	≈30 BeV	protons	Brookhaven National Laboratory (Long Island) and CERN, Switzerland
		≈70 BeV	protons	Serpukhov, U.S.S.R.
Strong-focusing synchrotron	"	≈200-400 BeV protons		Weston, Illinois (in planning and design stage)



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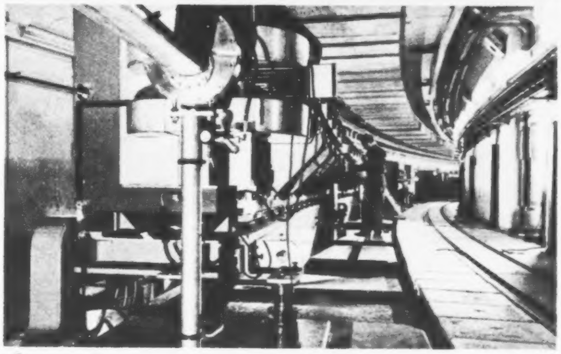

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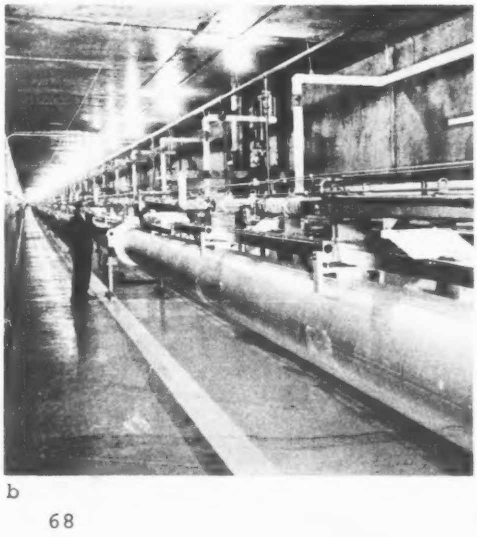

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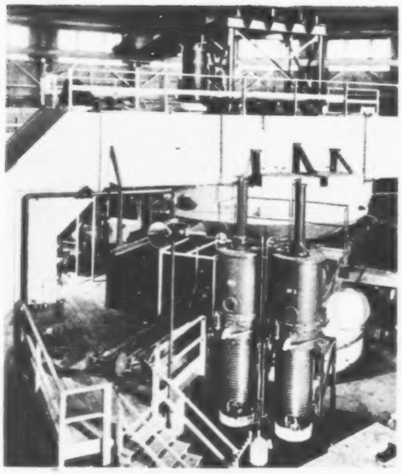
a. b. The Stanford "Linac" (linear accelerator).

c. d. The CERN proton synchotron at Geneva. The evacuated ring in which the protons are accelerated is at the upper left of d.

e. The 184" cyclotron at Berkeley.

f. The Brookhaven Cosmotron, in operation from 1952 to 1967, has been superceded by larger accelerators.



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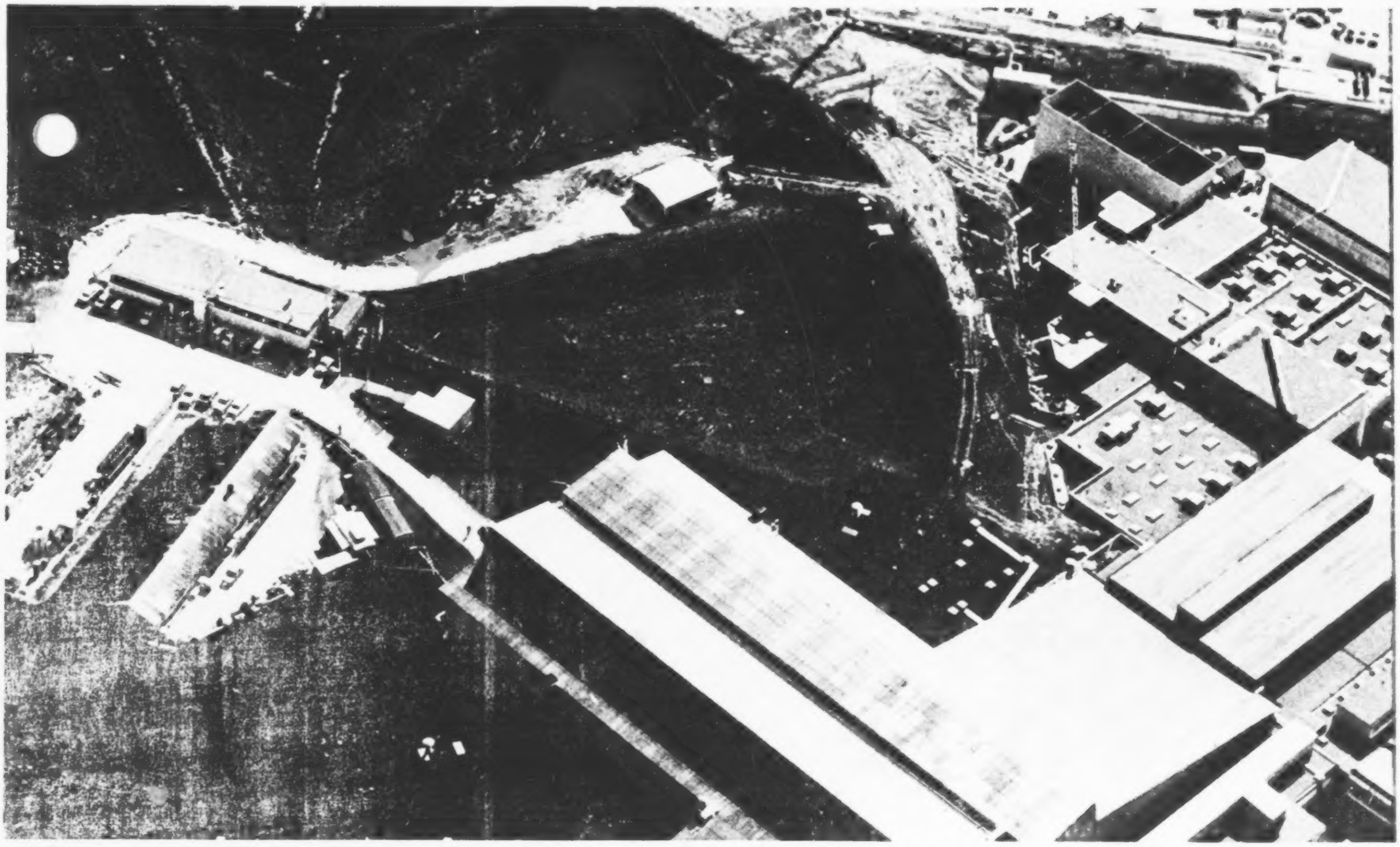
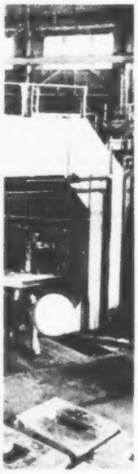
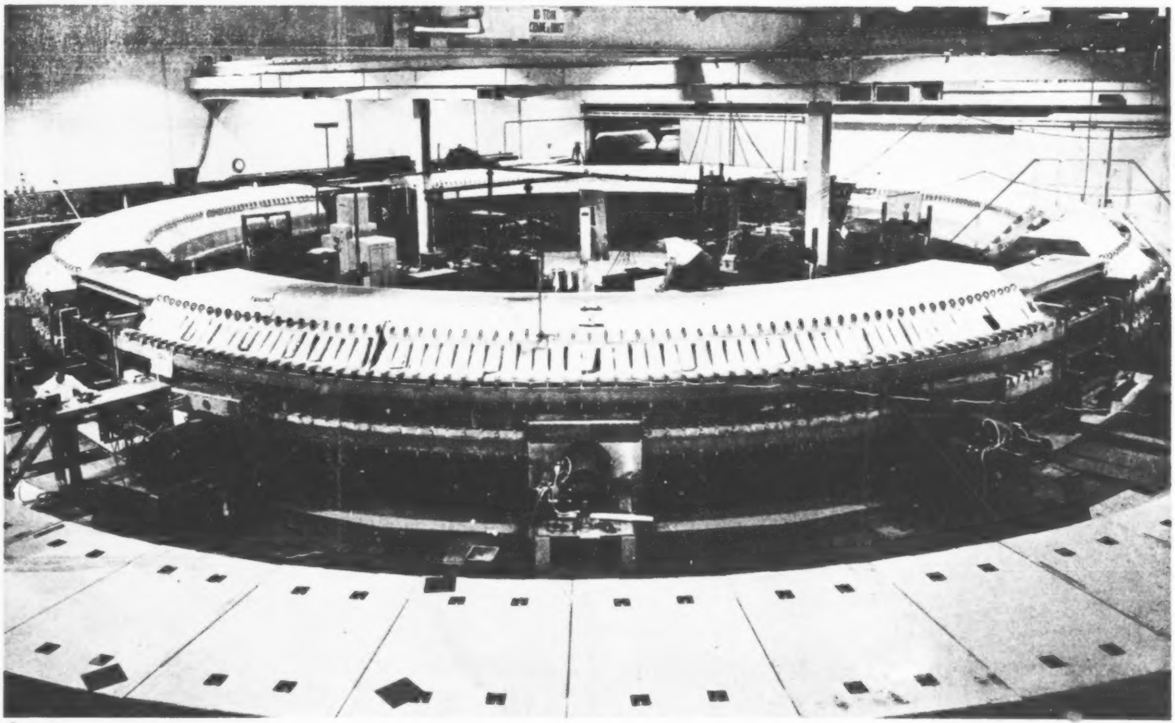






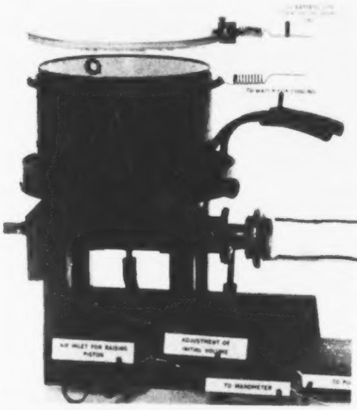
f

A large flask was connected here. It was pumped out, and then connected suddenly to the cloud chamber floor, causing it to drop very suddenly and produce a rapid expansion in the chamber.

completed by 1973 for approximately $240 million. Initial plans for an 800 to 1000 BeV machine are being formulated; construction should begin by 1971 at a cost of about $800 million. Why is a nation willing to budget such sums for larger and larger particle accelerators? What do we plan to discover with these high-energy machines? Basically, the answer is a simple one: we would like to find out as much as we can about the structure of nuclear particles and the nature of the forces holding them together.

With the discovery of the neutron in 1932 it was believed that three "elementary" particles act as the building blocks of matter: the proton, the neutron and the electron. We have mentioned the existence of new particles, such as neutrinos and antineutrinos. As high-energy accelerators became available, additional "elementary" particles were discovered one after another. In the appendix is a list of some of these

a. Wilson's cloud chamber.
b. Particle tracks in a cloud chamber.
c. The tiny bubble chamber, 3 cm long, invented by D.A. Glaser in 1952. Glaser was 26 at the time and 8 years later was awarded the Nobel Prize for his invention. (Note the particle track.)
d. The 200 cm Bubble Chamber Assembly at the Brookhaven National Laboratory.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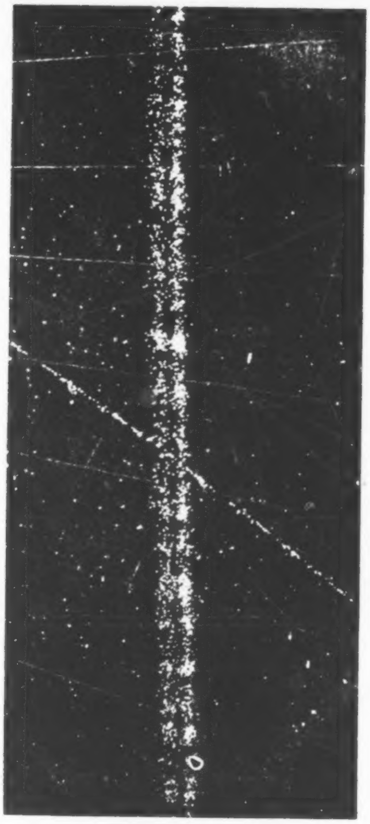
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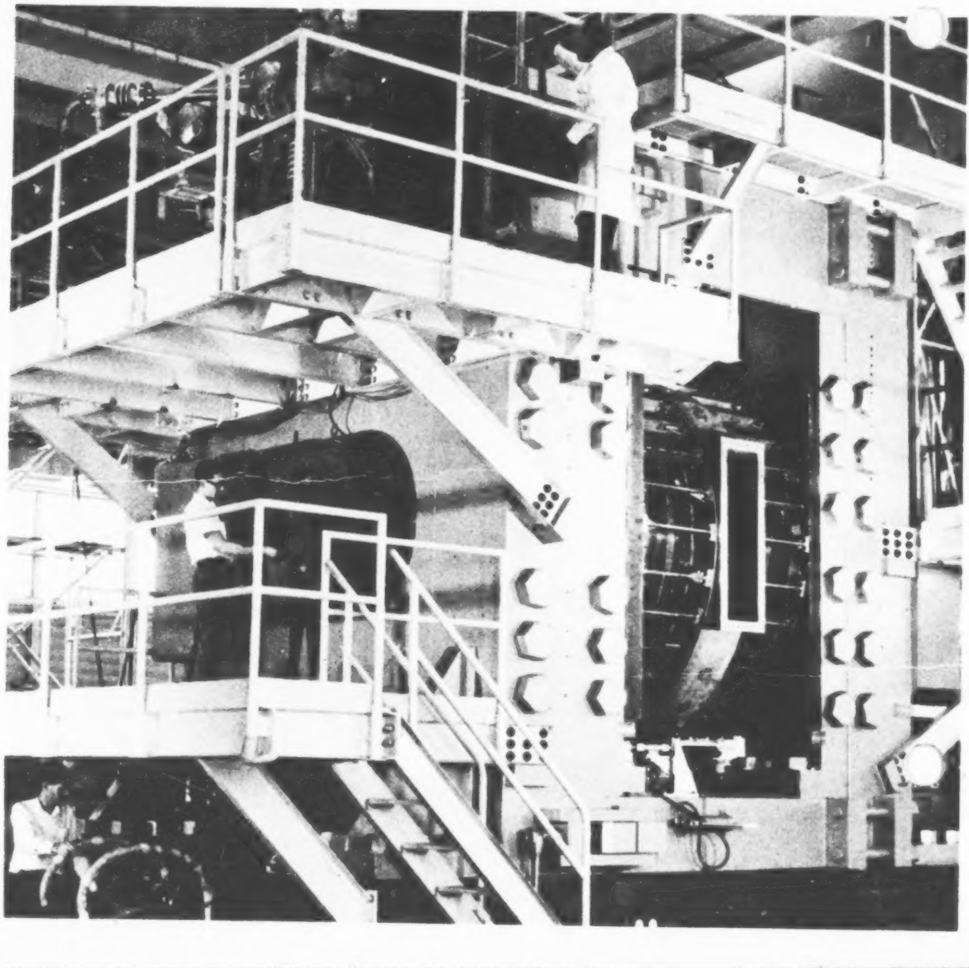
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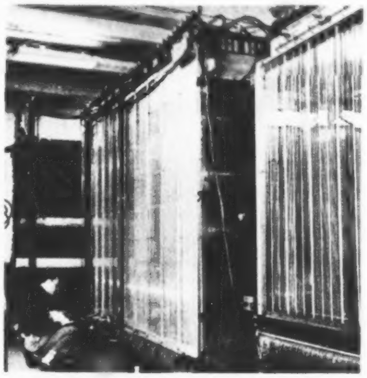
particles: they are grouped into "families" according to their properties. Most of these particles exist only very briefly—typical lifetimes are of the order of 10^{-8} second or less. A whole new field, "high-energy physics," has evolved and the high-energy physicist of today is trying to detect some order and structure into which he can fit the large number of "elementary" particles he has discovered.

How do we detect these particles? We have already mentioned a number of methods by which we can observe and measure radioactivity. They include the Geiger counter (Sec. 19.3), the electroscope and electrometer employed since the early days of radioactivity, and the Wilson cloud chamber. In addition we now have various types of ionization chambers, scintillation counters, photographic emulsions, semiconductor devices, bubble chambers and spark chambers, some of which are displayed on these pages. One of the additional units in this course, Elementary Particles, describes the discoveries made with these detection devices.



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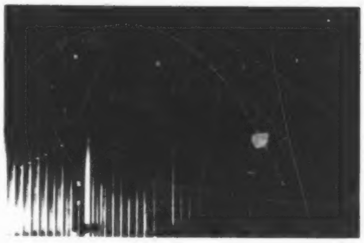

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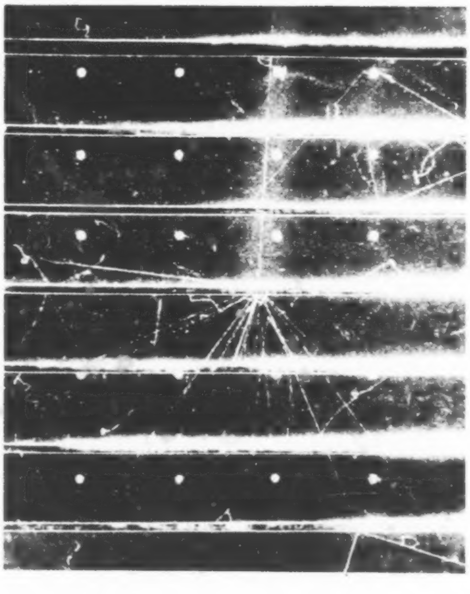
e. The viewing of a projected, enlarged photograph of particle tracks in a bubble chamber.
f. g. h. A spark chamber. A charged particle passing through the chamber ionizes the gas along its path between the plates. When high voltage is applied, sparks jump between the plates along the ionized tracks, thus revealing the paths of the particles.

e

h



Summary 23.8

1. The use of accelerators has led to thousands of nuclear reactions of many types.

2. The ancient dream of the alchemist has come true. We are now able to produce artificially almost any nuclide we want; in all cases, charge (Z) and mass number (A) must be conserved.

3. Neutron-producing reactions are especially important, because the neutrons themselves can induce a great variety of reactions.

Q10 Why can low-energy α particles cause transmutations only in nuclei of low mass?

Q11 Why are protons more effective projectiles for promoting nuclear reactions than α particles or heavy ions?

23.8 Nuclear reactions. The development of the cyclotron and other particle accelerators led to great advances in the study of nuclear reactions. Nearly all of the stable nuclides have been bombarded with protons, deuterons, α particles, neutrons and γ rays, and hundreds of nuclear reactions have been examined. Examples of reactions induced by α particles and protons have already been discussed.

Since the first known alchemical writings during the third or fourth centuries A.D., and throughout the historical development of chemistry, the dream of "making gold" has always been present. In most nuclear reactions one element is changed into another: the ancient dream of the alchemist has come true, but it is unlikely to make a fortune for anyone. Now we are finally able to transmute various elements into gold, but such transformations are a far cry, both in method and purpose, from the attempts of the ancient alchemists.

We discuss the transmutation into gold only as an example of a nuclear reaction; a more useful reaction is the transmutation of gold into something else—for example:

$${}_{79}\mathrm{Au}^{197} + {}_{0}\mathrm{n}^{1} \rightarrow {}_{80}\mathrm{Hg}^{198} + {}_{-1}\mathrm{e}^{0},$$

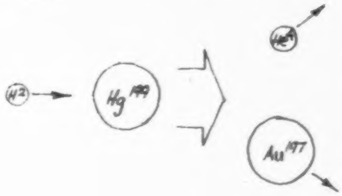
which is used to obtain very pure samples of a single mercury isotope.

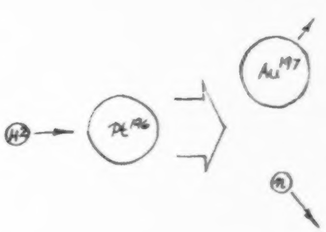
Gold has only one stable isotope—${}_{79}\mathrm{Au}^{197}$; all other gold isotopes are radioactive and are not found in nature. We will illustrate two types of nuclear reactions induced by deuterons, both resulting in gold. One is

$${}_{1}\mathrm{H}^{2} + {}_{80}\mathrm{Hg}^{199} \longrightarrow {}_{79}\mathrm{Au}^{197} + {}_{2}\mathrm{He}^{4}.$$

The other is

$${}_{1}\mathrm{H}^{2} + {}_{78}\mathrm{Pt}^{196} \longrightarrow {}_{79}\mathrm{Au}^{197} + {}_{0}\mathrm{n}^{1}.$$





In both cases we need an accelerator to produce high-energy deuterons; in bombarding a mercury isotope we produce α particles besides our desired gold. Bombarding platinum we produce neutrons in addition to the gold.

T47: Nuclear equations

L6-4: Nuclear reactions

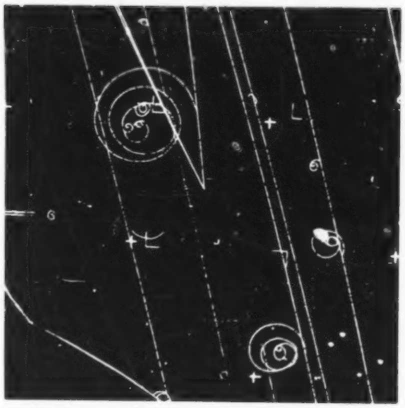
The last reaction, in which a neutron was produced, is an example of reactions which have become especially important because of the usefulness of the neutrons produced. Neutrons can result when nuclei are bombarded with protons, deuterons or α particles, as in the reactions:

$${}_{28}\mathrm{Ni}^{58} + {}_{1}\mathrm{H}^{1} \longrightarrow {}_{29}\mathrm{Cu}^{58} + {}_{0}\mathrm{n}^{1},$$

$${}_{6}\mathrm{C}^{12} + {}_{1}\mathrm{H}^{2} \longrightarrow {}_{7}\mathrm{N}^{13} + {}_{0}\mathrm{n}^{1},$$

$${}_{4}\mathrm{Be}^{9} + {}_{2}\mathrm{He}^{4} \longrightarrow {}_{6}\mathrm{C}^{12} + {}_{0}\mathrm{n}^{1}.$$

The neutrons produced by bombardment can, in turn, be used to induce nuclear reactions. Neutrons are especially effective as "bullets" because they have no electric charge. They are not subject to repulsive electrostatic forces in the neighborhood of a positively charged nucleus, and are therefore more likely to penetrate nuclei than are protons, deuterons or α particles. Because of the neutron's lack of electrical charge many more reactions have been induced by neutrons than by any other kind of particle. Fermi was the first to undertake a systematic program of research involving the use of neutrons as projectiles in nuclear reactions. He bombarded many elements, from the lightest to the heaviest, with neutrons, and studied the properties of the nuclides produced. The research described in the prologue to Unit 1 was done as part of this program.



In this bubble chamber picture, a neutron is produced at bottom center and in turn causes a reaction near the center. (Neutral particles do not leave tracks in bubble chambers.)

A typical neutron-induced reaction, once again resulting in gold, is:

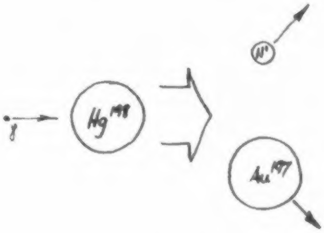
$$_0n^1 + {}_{80}Hg^{198} \longrightarrow {}_{79}Au^{197} + {}_1H^2.$$

In a very common type of neutron-induced reaction the neutron is captured and a γ ray is emitted, as in the following example:

$$_0n^1 + {}_{78}Pt^{196} \longrightarrow {}_{78}Pt^{197} + \gamma.$$

Note that since there is no change in the atomic number the element remains the same. An isotope of the target nucleus is produced with a mass number greater by one unit than that of the target nucleus. The new nucleus is produced in an excited state and returns to its lowest energy state by emitting one or more γ rays.

Atomic nuclei can also undergo reactions when bombarded with γ rays; an example, once again resulting in gold, is the reaction:



$$\gamma + {}_{80}Hg^{198} \longrightarrow {}_{79}Au^{197} + {}_1H^1.$$

In this case the energy of the γ ray excites the mercury target nucleus which becomes unstable, ejects a proton and becomes a gold nucleus.

The amount of gold produced by the above reactions is very small; we simply tried to illustrate some typical artificial transmutations. The examples we have given barely suggest the rich variety of such reactions that have been observed.

SG 23.10
SG 23.11

The products of these reactions may change as the energy of the bombarding particles changes. Nuclear reactions are important, not only because they indicate our ability to produce new nuclides, but also because they provide important data about nuclear structure. A model of nuclear structure, to be successful, must enable us to predict the results of these nuclear reactions, just as a successful model of atomic structure must allow us to predict the results of chemical reactions.

Q12 Is this statement true or false: "All nuclear reactions involve transmutation from one element to another"?

Q13 What property of neutrons makes them particularly useful for provoking nuclear reactions?

Q14 Complete the following equation for a nuclear reaction:
$_{13}Al^{27} + {}_{1}H^{2} \longrightarrow {}_{0}n^{1} + {}_{?}Si^{?}$.

Summary 23.9
1. Many of the nuclear reactions result in radioactive products.

2. These artificially-produced radioactive nuclides usually emit electrons or positrons.

3. Almost 1200 unstable nuclides have been prepared and identified.

23.9 Artificially induced radioactivity. In the discussion of nuclear reactions we have passed over an interesting discovery. We have shown that the capture of a neutron by platinum 196 results in platinum 197 and the emission of a γ ray. As seen from Table 22.1 six different isotopes of platinum are found in nature—but platinum 197 is not among these. The question arises: is the platinum 197 produced by neutron capture stable? The answer is no; it is radioactive and decays by the emission of a β particle to gold 197, becoming the only stable gold isotope:

$$_{78}Pt^{197} \longrightarrow {}_{79}Au^{197} + {}_{-1}e^{0} + \bar{\nu}\ .$$

The half life of platinum 197 is 20 hours.

The production of radioactive platinum 197 in a nuclear reaction is an example of artificially induced radioactivity, discovered in 1934 by Irène Curie and F. Joliot. They were studying the effects of α particles on the nuclei of light elements. When they bombarded boron, magnesium and aluminum with α particles from polonium, they observed protons and neutrons, as expected. But, in addition to these particles, positive electrons, or positrons, also were observed. The positron is a particle whose mass is the same as that of the electron, and whose charge has the same magnitude but opposite sign to that of the electron.

This is one of the earliest records of a "shower" of electrons and positrons, and shows their tracks curving in opposite directions in a strong magnetic field. The shower was caused by cosmic rays and was recorded in this Wilson cloud chamber photo taken at an altitude of 4.3 km.

The positron had been discovered earlier by C. D. Anderson in 1932 while studying photographs of cosmic ray tracks in a cloud chamber. Cosmic rays are highly penetrating radiations which originate outside the earth and consist of protons, F53: Positron - electron annihilation

electrons, neutrons, photons and other particles. Employing a cloud chamber situated in a magnetic field, Anderson observed some tracks which could have been produced only by particles having the mass and magnitude of charge of the electron, but the curvature was opposite in direction to that of electron tracks; Anderson concluded that the particles producing them must have been positively charged.

The production of positrons along with neutrons as a result of the bombardment of a light element with α particles seemed to indicate that a new type of nuclear reaction could occur in which a neutron and a positron were emitted. But further experiments by Curie and Joliot showed that the light-element targets continued to emit positrons even after the source of the α particles had been removed. When the rate of emission of the positrons was plotted against the time after the removal of the α particle source, curves were obtained, for each target, similar to the curves obtained in natural β radioactivity. The results seemed to show that an initially stable nuclide had been changed into a radioactive one. In the case of the bombardment of $_{13}Al^{27}$ by α particles, which produced neutrons as well as the new radioactive material, the reaction expected would produce an isotope of phosphorous:

$$_{13}Al^{27} + {}_{2}He^{4} \xrightarrow{?} {}_{0}n^{1} + {}_{15}P^{30}.$$

Curie and Joliot made chemical separations similar to those made in the study of the naturally radioactive elements, and showed that the target, after bombardment, contained a small amount of phosphorus that was radioactive. Now, phosphorus occurs in nature only as $_{15}P^{31}$; natural $_{15}P^{31}$ has an isotope abundance of 100 percent and no isotope of phosphorus with mass number 30 had ever been found to occur naturally. It was reasonable to suppose that if P^{30} were made in a nuclear reaction it would be radioactive and would decay in the following manner:

$$_{15}P^{30} \longrightarrow {}_{14}Si^{30} + {}_{1}e^{0} + \nu,$$

where $_{14}Si^{30}$ is a known isotope of silicon, $_{1}e^{0}$ represents a positron ($_{-1}e^{0}$ represents an electron), and ν is a neutrino. The half-life of P^{30} turned out to be 2.5 minutes.

F. Joliot and Irene Curie in their laboratory. They were married in 1926.

This kind of β decay implies that a proton in the nucleus is transformed into a neutron and positron (and a neutrino):

$$_{1}p^{1} \longrightarrow {}_{0}n^{1} + {}_{+1}e^{0} + \nu.$$

23.9

After the discovery that the bombardment of light nuclides by α particles can lead to radioactive products, it was found that nuclear reactions induced by protons, deuterons, neutrons and photons can also result in radioactive products. As in the case of the natural radionuclides, an artificial radionuclide can be characterized by its half-life and the type of radiation it emits. When the products of nuclear reactions are radioactive they can be traced in chemical separations by means of their characteristic half-lives or decay products. Otherwise they could not be traced because of the very small amounts involved—often less than a millionth of a gram. The special branch of chemistry that deals with the separation and identification of the radioactive products of nuclear reactions is called radiochemistry and has become an important part of nuclear science. The breadth of this field is indicated by the fact that since 1935 about 1200 artificially radioactive nuclides have been made and identified.

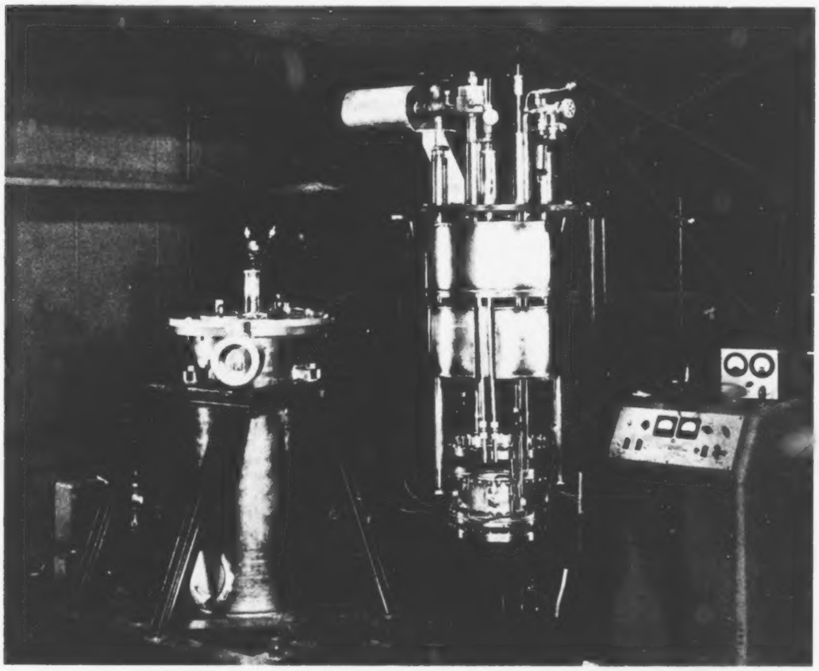
SG 23.12

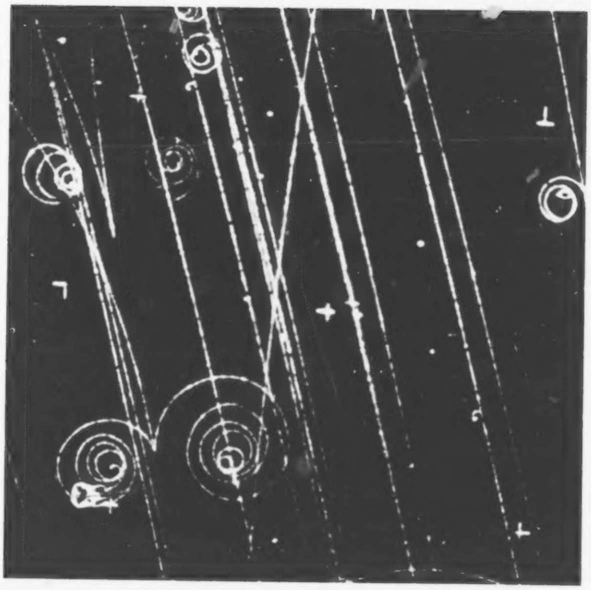
SG 23.13

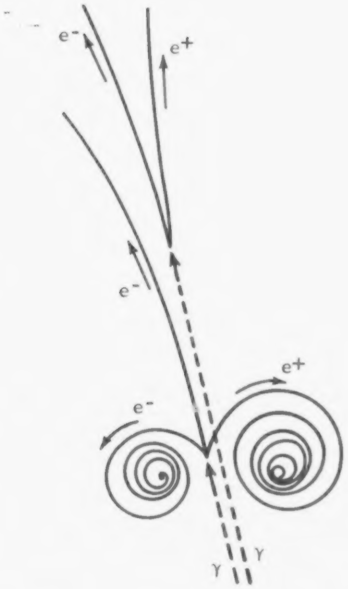
Q15 Complete the following equation for a positive β-decay:

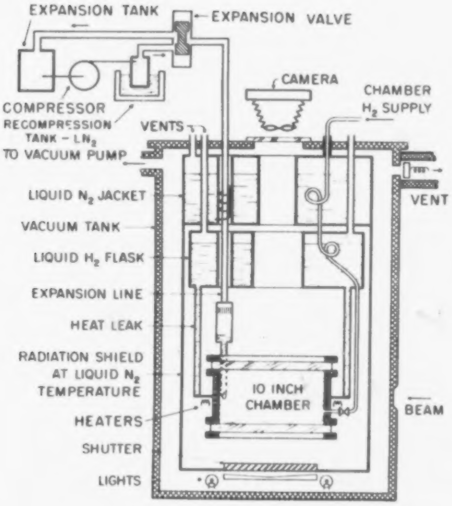
$$_7N^{13} \longrightarrow {}_1e^0 + {}_?C^?$$

How many neutrons and protons were there in the nitrogen nucleus before decay? How many in the carbon nucleus afterward?








EXPANSION TANK
EXPANSION VALVE
CAMERA
CHAMBER H_2 SUPPLY
COMPRESSOR
RECOMPRESSION TANK – LN_2
VENTS
TO VACUUM PUMP
VENT
LIQUID N_2 JACKET
VACUUM TANK
LIQUID H_2 FLASK
EXPANSION LINE
HEAT LEAK
RADIATION SHIELD AT LIQUID N_2 TEMPERATURE
10 INCH CHAMBER
BEAM
HEATERS
SHUTTER
LIGHTS

The bubble chamber photo at the upper left illustrates one of the most important discoveries of modern physics, the interconversion of energy and matter (Chapters 9 and 20). The diagram above shows the significant tracks of that photo. In the upper left an electron-positron pair is formed by a gamma ray (not visible in bubble chamber pictures) interacting with a hydrogen nucleus. An applied magnetic field causes the electron and the positron to be deflected in opposite directions. (Can you determine the direction of the magnetic field?)

In the lower left of the same photo a gamma ray forms another electron-positron pair; the additional electron (third track, upward) was knocked out of a hydrogen atom during this process.

The bubble chamber photo was taken in a 10" liquid hydrogen bubble chamber at the Lawrence Radiation Laboratory of the University of California. The chamber is shown at the far left with the liquid nitrogen shield removed. The accompanying diagram gives some of the details of the bubble chamber and its auxiliary equipment.

Study Guide

23.1 Why would it be difficult to explain ${}_{92}U^{235}$ as a mixture of alpha particles and electrons? 235 is not divisible by 4

23.2 On the basis of the proton-electron hypothesis of nuclear composition, how many protons would you expect to find in the ${}_{92}U^{235}$ nucleus? How many electrons? 235 protons, 143 electrons.

23.3 Complete the following nuclear equations:

(a) ${}_{5}B^{10} + {}_{2}He^{4} \longrightarrow ({}_{6}C^{13}) + {}_{1}H^{1}$.

(b) ${}_{11}Na^{23} + {}_{2}He^{4} \longrightarrow ({}_{12}Mg^{26}) + {}_{1}H^{1}$.

(c) ${}_{13}Al^{27} + {}_{2}He^{4} \longrightarrow ({}_{14}Si^{30}) + {}_{1}H^{1}$.

(d) $({}_{16}S^{32}) + {}_{2}He^{4} \longrightarrow {}_{17}Cl^{35} + {}_{1}H^{1}$.

(e) $({}_{19}K^{39}) + {}_{2}He^{4} \longrightarrow {}_{20}Ca^{42} + {}_{1}H^{1}$.

23.4 Complete the following nuclear equations:

(a) ${}_{3}Li^{6} + {}_{1}H^{1} \longrightarrow {}_{2}He^{4} + ({}_{2}He^{3})$.

(b) ${}_{4}Be^{9} + {}_{1}H^{1} \longrightarrow {}_{2}He^{4} + ({}_{3}Li^{6})$.

(c) ${}_{4}Be^{9} + {}_{1}H^{1} \longrightarrow ({}_{4}Be^{8}) + {}_{1}H^{2}$.

(d) ${}_{5}B^{11} + {}_{2}He^{4} \longrightarrow {}_{7}N^{14} + ({}_{0}n^{1})$.

23.5 Complete the following nuclear equations:

(a) $Al^{27} + {}_{0}n^{1} \longrightarrow Al^{28} + (\gamma)$.

(b) $Al^{27} + {}_{1}H^{2} \longrightarrow {}_{1}H^{1} + (Al^{28})$.

(c) $Al^{27} + {}_{1}H^{1} \longrightarrow {}_{2}He^{4} + (Mg^{24})$.

(d) $Al^{27} + {}_{1}H^{2} \longrightarrow {}_{2}He^{4} + (Mg^{25})$.

What aspect of nuclear reactions do equations (b) and (d) illustrate?
The same nuclide bombarded by different particles will yield different products.

23.6 Explain briefly why the maximum speed gained by nitrogen nuclei in collisions with neutrons is approximately an order of magnitude less than that gained by hydrogen nuclei in collisions with neutrons.
Nitrogen nuclei are in order of magnitude more massive than hydrogen.

23.7 One major disadvantage of indirect methods of measurement is that the experimental uncertainty is often increased. If Chadwick had measured a maximum speed of 3.2×10^{9} cm/sec for hydrogen nuclei (a shift of only 3%), and 4.7×10^{8} cm/sec for nitrogen nuclei (no shift), what would be the calculated mass of the neutron? By what percentage would the calculated mass of the neutron change due to the 3% shift in the speed measurement?
1.24 amu 6.9%

23.8 Indicate the mass number A, the atomic number Z, the number of protons and the number of neutrons for each of the following nuclei: (Make a similar table in your notebook.)

	A	Z	protons	neutrons
H^1	1	1	1	0
H^2	2	1	1	1
He^4	4	2	2	2
Li^7	7	3	3	4
C^{13}	13	6	6	7
U^{238}	238	92	92	146
Th^{234}	234	90	90	144
Th^{230}	230	90	90	140
Pb^{214}	214	82	82	132
Pb^{206}	206	82	82	124

23.9 How many electrons are there in a neutral atom of

(a) platinum 196? 78
(b) gold 197? 79
(c) mercury 198? 80

23.10 Complete the following nuclear equations:

(a) ${}_{11}Na^{23} + {}_{1}H^{2} \longrightarrow {}_{1}H^{1} + ({}_{11}Na^{24})$.

(b) ${}_{11}Na^{23} + {}_{0}n^{1} \longrightarrow \gamma + ({}_{11}Na^{24})$.

(c) ${}_{12}Mg^{24} + {}_{0}n^{1} \longrightarrow {}_{1}H^{1} + ({}_{11}Na^{24})$.

(d) ${}_{12}Mg^{26} + {}_{1}H^{2} \longrightarrow {}_{2}He^{4} + ({}_{11}Na^{24})$.

What aspect of nuclear reactions do these equations illustrate?

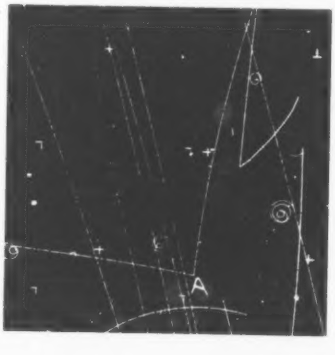
23.11 Describe the following reactions in words: description

$${}_{13}Al^{27} + {}_{0}n^{1} \longrightarrow {}_{12}Mg^{27} + {}_{1}H^{1}.$$

$${}_{12}Mg^{27} \longrightarrow {}_{13}Al^{27} + {}_{-1}e^{0} + \bar{\nu} + \gamma;\ T = 9.5\ \text{min.}$$

23.12 It is often necessary to infer information in the absence of direct evidence. Thus when a hunter following the tracks of a rabbit in the snow finds that the tracks suddenly stop with no evidence of other tracks or of hiding places, he may infer something about the possible presence of owls or eagles.

The bubble chamber photograph at the right shows, among other things, the tracks of two nuclear particles that originate or terminate at point A. Describe the interaction that occurs at point A in terms of your knowledge of the law of conservation of momentum. discussion



23.13 How do you think the discovery of artifically radioactive nuclides helped the development of theories of nuclear structure? discussion

Chapter 24 Nuclear Energy, Nuclear Forces

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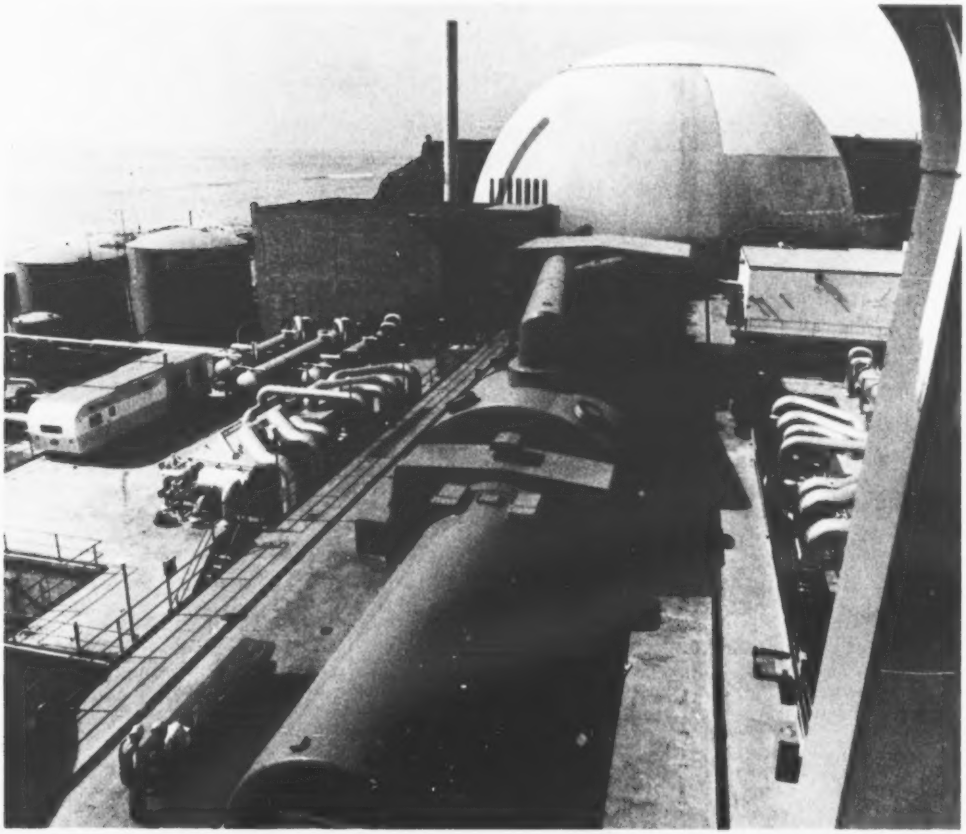


24.1 Conservation of energy in nuclear reactions. In the discussion of nuclear reactions in the last chapter the emphasis was on the transformations of nuclei and on the properties of the nuclides formed. But there is another property of these reactions that is important—the absorption or release of energy. The way in which we wrote the equations for nuclear reactions is analogous to that used for chemical equations, and we can extend the analogy to the treatment of the energy relations in nuclear reactions. In some chemical reactions energy must be supplied from the outside to keep the reaction going, while in others energy is liberated. The formation of water from oxygen and hydrogen is an example of a reaction in which energy is liberated; the reaction between these two gases is usually violent and heat is given off. We may conclude that the water formed has less energy than did the substances of which the water is made. When water is decomposed by electrolysis, electrical energy must be supplied by passing a current through the water, and the products of the reaction—the oxygen and hydrogen liberated—have more energy than the water.

Summary 24.1
1. Nuclear reactions can be analyzed in terms of the masses and energies before and after the reaction.

2. Any change in rest mass is associated with a kinetic energy change in accordance with Einsteins mass-energy relation: $\Delta E = \Delta mc^2$

In both cases we neglect the small amount of energy which may be required to start the reaction.

Chemical reactions can be analyzed quantitatively in terms of the amounts of the reacting materials and of the products formed, and in terms of the energy (thermal or electrical) absorbed or liberated. In an analogous way a nuclear reaction can be analyzed in terms of the masses and the energies of the nuclei and particles before and after the reaction. Nuclear reactions may absorb energy or they may liberate energy. The amount of energy absorbed or emitted per nucleus involved is greater by a factor of a million or more than the amount involved per atom in a chemical reaction. Since mass and energy are equivalent, large release of energy will be accompanied by changes in the total rest mass of the interacting nuclei. The relation $E = mc^2$ plays an important part in analyzing nuclear reactions. Nuclear fission and nuclear fusion (discussed later in this chapter) are two special kinds of nuclear reactions in which the energy release is much greater, by a factor of 10 to 100, than that in other nuclear reactions. It is the exceptionally large energy release in these two types of reactions that makes them important in industrial and military applications.

It would be a good idea to reread pp. 102-105 in Unit 5, to review the relativistic relationship of mass and energy. Two important ideas for this chapter are: a) the mass of a moving body is greater than the rest mass by KE/c^2, and b) a particle at rest has a rest energy of m_0c^2.

In this chapter we shall examine the mass and energy relations in nuclear reactions and some of their consequences. This study will show how some of the ideas and experimental information of the last three chapters are linked together.

See "Conservation Laws" in Project Physics Reader 6.

Q1 **Is energy always liberated in a nuclear reaction?**

In this nuclear-electric power plant, a controlled fission reaction supplies heat energy for operation of a steam turbine which drives an electrical generator.

Summary 24.2
1. For each atomic species, the atomic mass is smaller than the sum of the rest masses of the constituent particles.

2. The loss in rest mass is equivalent to the energy release from the nucleus. This energy release is called the binding energy of the nucleus.

24.2 The energy of nuclear binding. Our concepts of atomic and nuclear structure—that an atom consists of a nucleus surrounded by electrons and that the nucleus is made up of protons and neutrons—led to a fundamental question: is the mass of an atom equal to the sum of the masses of the protons, neutrons and electrons that make up the atom? This question can be answered because the masses of the proton, the neutron and the electron are known, as are the masses of nearly all the atomic species. A survey of the known atomic masses shows that, for each kind of atom, the atomic mass is always less than the sum of the masses of the constituent particles in their free state. The simplest atom containing at least one proton, one neutron and one electron is deuterium, ${}_1H^2$; in this case we have for the masses:

As early as 1927 Aston concluded from his measurements with a mass spectrograph: if two light nuclei combine to form a heavier one, the new nucleus weighs less than the sum of the original ones.

rest mass of one proton = 1.007276 amu
rest mass of one neutron = 1.008665
rest mass of one electron = 0.000549

total rest mass of constituent particles in free state = 2.016490

rest mass of deuterium atom = 2.014102
difference (Δm) = 0.002388 amu.

Although the difference Δm in rest mass may appear small, it corresponds to a significant energy difference because of the factor c^2 in the relation $E = mc^2$. The difference ΔE in energy should correspond to the difference in mass according to the relation: $\Delta E = \Delta mc^2$. The conversion factor from atomic mass (expressed in amu) to energy (expressed in MeV) is

$$1 \text{ amu} = 931 \text{ MeV}.$$

$$1 \text{ amu} = 1.66 \times 10^{-27} \text{ kg}$$

$$\begin{aligned}\Delta E &= \Delta mc^2 \\ &= (1 \text{ amu})(1.66 \times 10^{-27} \tfrac{\text{kg}}{\text{amu}}) \\ &\quad \times (3 \times 10^8 \tfrac{\text{m}}{\text{sec}})^2 \\ &= 14.9 \times 10^{-11} \text{ joules} \\ &= \frac{14.9 \times 10^{-11} \text{ joules}}{1.6 \times 10^{-13} \text{ joules/MeV}} \\ &= 931 \text{ MeV}\end{aligned}$$

If a proton and neutron combine, then a rest mass of 0.002388 amu should be "lost," appearing as 0.002388 amu × 931 MeV/amu = 2.22 MeV of kinetic energy.

The result calculated from the change in rest mass can be compared with the result of a direct experiment. When hydrogen is bombarded with neutrons, a neutron can be captured in the reaction:

$$ {}_0n^1 + {}_1H^1 \longrightarrow {}_1H^2 + \gamma. $$

Since there are no fragments with large kinetic energy, the "missing" mass of 0.002388 amu must be carried away by the γ radiation. The energy of the γ ray has been determined, and is 2.22 MeV, as predicted! The inverse reaction, in which deuterium is bombarded with γ rays, has also been studied:

$$_1H^2 + \gamma \longrightarrow {}_1H^1 + {}_0n^1 .$$

When the energy of the γ rays is less than 2.22 MeV, no reaction occurs. But if we use γ rays of energy 2.22 MeV or greater, the reaction does occur: a proton and a neutron are detected. In the "capture" of a neutron by the nucleus $_1H^1$, energy is liberated. In the inverse reaction ($_1H^2$ bombarded with γ rays) energy is absorbed. The energy, 2.22 MeV, is called the binding energy of the deuteron. It is the energy released when a proton and neutron combine to form a nucleus. (The binding energy is also, therefore, the amount of energy which would be needed to break the deuteron up again.)

Q2 When energy is "liberated" during a nuclear reaction, what becomes of it?

24.3 Stability and binding energy. The calculation made for deuterium can be extended to the other nuclear species. In practice, physicists make such calculations for atoms rather than for atomic nuclei, because experimental values of atomic masses are known from mass-spectrographic measurements. Since an atom contains electrons (in the outer shells) as well as the protons and neutrons in the nucleus, the mass of the electrons must be included in the calculations. It is convenient to do so by combining the mass of one proton and one electron and using the mass of one hydrogen atom for the combination. (The binding energy and equivalent mass involved in the formation of a hydrogen atom from a proton and an electron may be neglected—it is only 13 eV as compared to nuclear binding energies which are several MeV per nuclear particle.) The following example illustrates the calculations necessary to find the binding energy of an atom. We compare the actual mass of a carbon 12 atom with the total mass of its separate component particles:

Summary 24.3
1. The binding energy is calculated directly from the difference in rest mass.

2. The stability of a nucleus depends on its average binding energy per nucleon.

rest mass of 6 hydrogen atoms (includes 6 protons and 6 electrons)	$6 \times 1.007825 =$	6.046950 amu
rest mass of 6 neutrons	$6 \times 1.008665 =$	6.051990
total rest mass of particles		12.098940
rest mass of carbon 12		12.000000
difference in rest mass	$\Delta m =$	0.098940 amu

$$0.098940 \text{ amu} \times 931 \text{ MeV/amu} = 92.1 \text{ MeV}.$$

In the same manner one can calculate the binding energy of any stable atom. Figure 24.1a shows how the binding energy for

SG 24.1

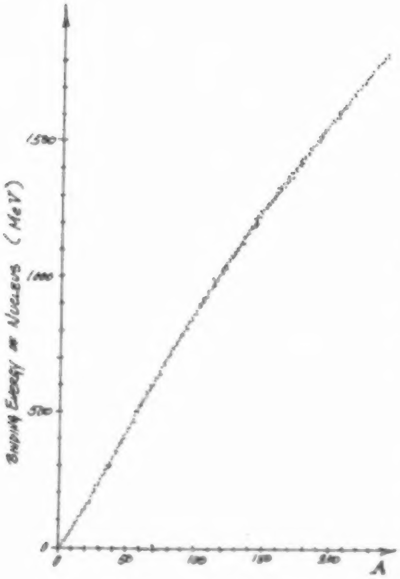


Fig. 24.1a Binding energy as a function of A.

stable nuclides increases with increasing atomic mass, as more particles are added to the nucleus. Such data have important implications for the structure of the nucleus. This can be seen more clearly if we calculate the average binding energy per particle. In the case of carbon 12 example, we found the total binding energy to be 92.1 MeV. Since we are dealing with 12 particles inside the nucleus (6 protons and 6 neutrons), the average binding energy per particle is 92.1 MeV/12 or 7.68 MeV. In Fig. 24.1b the values of average binding energy per particle (in MeV) are plotted against the number of particles (mass number A).

The binding energy per particle starts with a low value for deuterium, and then increases rapidly. Some nuclei, for example He^4, C^{12} and O^{16} have exceptionally high values as compared with their neighbors. More energy would have to be supplied to remove a particle from one of them than from one of their neighbors. We would therefore expect He^4, C^{12} and O^{16} to be exceptionally stable. There is evidence in favor of this conclusion: for example, the fact that the four particles making up the He^4 nucleus are emitted as a single unit, the α particle, in radioactivity. The curve has a broad maximum extending from approximately A = 50 to A = 90 and then drops off for the heavy elements. Thus, $_{29}Cu^{63}$ has a binding energy per particle of about 8.75 MeV, while $_{92}U^{235}$, near the high-A end of the curve, has a value of 7.61 MeV. The nuclei in the neighborhood of the maximum of the curve, for example, those of copper, should be more difficult to break up than those of uranium.

SG 24.2

T48: Binding energy curves

Notice the unusually high position of He^4 (the dot near 7.1 MeV). This is related to its unusually great stability.

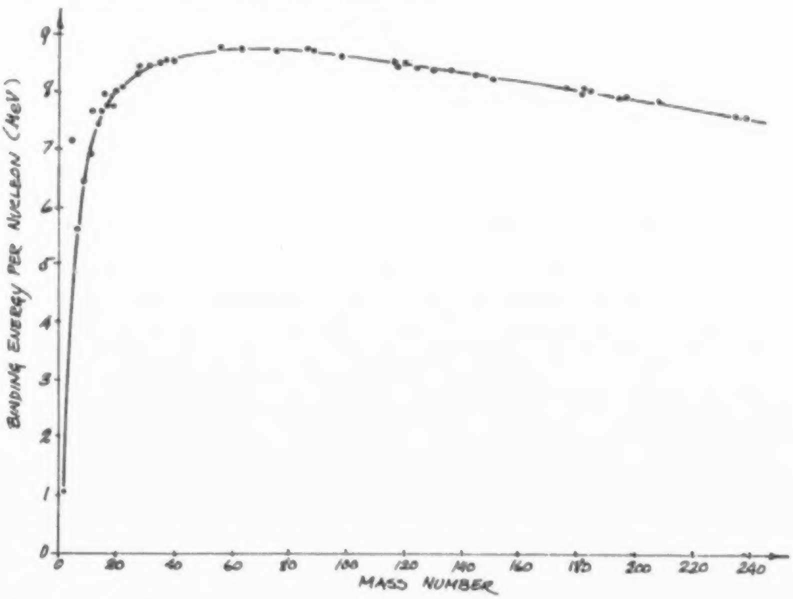


Fig. 24.1b Average binding energy per particle as a function of the number of particles A.

Now it is clear why atomic masses are not exactly whole number multiples of the mass of a hydrogen atom, even though nuclei are just collections of identical protons and neutrons. The total rest mass of a combination of these particles is reduced by an amount corresponding to the binding energy, and the average binding energy varies from nuclide to nuclide.

With the information we now have about the nuclear binding energy, we shall be able to get an understanding of the energy relations in nuclear reactions. (There are other important implications of the average binding energy curve, Fig. 24.1b which we shall mention later.)

Q3 Which would be more stable, a nuclide with a high total binding energy, or a nuclide with a high average binding energy?

24.4 The mass-energy balance in nuclear reactions. In the previous section we used a very simple nuclear reaction to introduce the concept of binding energy. In this section we shall use a more complicated reaction—one in which the products are nuclei—to show an important relation between the binding energy and the energy liberated in a nuclear reaction.

Summary 24.4
1. The agreement between theoretical and experimental values for changes of mass and energy in nuclear reactions provides strong evidence for the validity of Einstein's mass-energy equation.

2. In any nuclear reaction, if the particles in the product nuclei are more tightly bound than those in the reacting nuclei, energy must have been released during the reaction.

We shall analyze the mass-energy balance in the reaction of a proton with lithium 7:

$$_1H^1 + {}_3Li^7 \longrightarrow {}_2He^4 + {}_2He^4 \; .$$

This reaction has historical interest: it was the first case of a nuclear disintegration brought about by artificially accelerated particles; and the analysis of the reaction provided one of the earliest quantitative tests of Einstein's mass-energy relation. The reaction was a good one to analyze because the masses of the proton, the α particle and the Li atom were known, and the kinetic energies of the proton and the two α particles could be measured accurately. The values of the atomic masses are:

rest mass of Li^7 = 7.016005 amu
rest mass of H^1 = 1.007825 amu
rest mass of He^4 = 4.002604 amu

The energy released may be calculated by finding the difference in rest masses before and after the nuclear reaction takes place. The difference in rest mass is 0.018622 amu, corresponding to 17.3 MeV. Since total energy is conserved, we can assume that 17.3 MeV of lost rest energy appears in the total kinetic energy of the two α particles emitted. In actual experiments the incident proton has kinetic energy so that the 17.3 MeV represents the difference between the kinetic energies of the two emitted α particles

before		after	
Li^7	7.016005	He^4	4.002604
H^1	1.007825	He^4	4.002604
	8.023830		8.005208

$$\begin{array}{r} 8.023830 \\ -\ \underline{8.005208} \\ \Delta m = 0.018622 \text{ amu} \end{array}$$

$$0.018622 \text{ amu} \times 931 \text{ MeV/amu}$$
$$= 17.3 \text{ MeV}$$

24.4 and the kinetic energy of the incident proton. The agreement between the energy calculated from the masses and the experimental value found from the kinetic energies shows that the mass-energy relation is valid. There is a genuine release of energy from the lithium atom at the expense of some of the rest mass of its fragments. This experiment was first done in 1932. Since then hundreds of nuclear transformations have been studied and the results have invariably agreed with the mass-energy relationships calculated by means of Einstein's equation $E = mc^2$.

The results obtained for the mass-energy balance in nuclear reactions can be related to information about binding energy contained in Fig. 24.1b. For example, the binding energy per particle of the lithium 7 nucleus $_3Li^7$ is 5.6 MeV. Since lithium 7 has seven particles in the nucleus, the total binding energy is 5.6 × 7 or 39.2 MeV, while the incident proton has no binding energy. The total binding energy of each α particle (He^4 nucleus) is 28.3 MeV; a total of 56.6 MeV for the two α particles. Since the nucleons in the product fragments are more tightly bound by 56.6—39.2 = 17.4 MeV, there will be 17.4 MeV of energy released in the reaction, appearing as kinetic energy of the fragments. This checks with the increase in kinetic energy found experimentally.

Since binding energy is the energy released in the formation of a nucleus, those nuclei with the highest binding energy have lost the most rest energy.

Analysis of many nuclear reactions verifies the general rule: When the total binding energy of the products exceeds that of the reactants, energy is liberated. That is, whenever the products of a nuclear reaction lie higher on the average binding energy curve, they have greater binding energy per particle and so energy is released in their formation.

The shape of the average binding energy curve indicates that there are two general processes which can release energy from nuclei: combining light nuclei into a more massive nucleus, or splitting up heavy nuclei into nuclei of medium mass. In either process the products would have greater average binding energy, so energy would be released. A process in which two nuclei join together to form a heavier nucleus is called nuclear fusion. A process in which a heavy nucleus splits into fragments of intermediate mass is called nuclear fission. Both fusion and fission have been shown to occur. Both processes can be made to take place slowly (as in a nuclear power plant) or very rapidly (as in a nuclear explosion).

Q4 Would breaking very heavy nuclei up into very light nuclei result in the liberation of energy?

24.5 Nuclear fission: discovery. The discovery of nuclear fission is an example of an unexpected result of great practical importance, obtained during the course of research carried on for reasons having nothing to do with the possible usefulness of the discovery. It is also an excellent example of the combined use of physical and chemical methods in nuclear research. After Joliot and Curie showed that the products of nuclear reactions could be radioactive, Fermi and his colleagues in Italy undertook a systematic study of nuclear reactions induced by neutrons. One of the purposes of this research was to produce new nuclides. Indeed, many new radioactive nuclides were made and their half-lives were determined. The kind of nuclear reaction used most successfully in this study was the capture of a neutron with the emission of a γ ray as discussed in Sec. 23.7. For example, when aluminum is bombarded with neutrons, the following reaction occurs:

A few of the problems encountered by Fermi in his work on these reactions were related in the Prologue to Unit 1.

Summary 24.5

1. Nuclear fission was discovered through experimentation involving the bombardment of uranium with neutrons in an attempt to form a new, heavier element.

2. The capture of a neutron by a uranium nucleus sometimes leads to fission and sometimes to β decay. The β decay of uranium was found to result in the formation of two new transuranium elements, neptunium and plutonium!

$$_0n^1 + {}_{13}Al^{27} \longrightarrow {}_{13}Al^{28} + \gamma\ .$$

Aluminum 28 is radioactive with a half-life of 2.3 minutes and decays by β emission into silicon:

$$_{13}Al^{28} \longrightarrow {}_{14}Si^{28} + {}_{-1}e^0 + \bar{\nu}\ .$$

As a result of the two reactions a nuclide is produced with values of Z and A each greater by one unit than those of the initial nucleus. Fermi thought that if uranium (the atomic species having the largest known value of Z) were bombarded with neutrons, a new element might be formed by the β decay of the heavier uranium isotope:

$$_0n^1 + {}_{92}U^{238} \longrightarrow {}_{92}U^{239} + \gamma\ ,$$

$$_{92}U^{239} \longrightarrow {}_{93}(?)^{239} + {}_{-1}e^0 + \bar{\nu}\ .$$

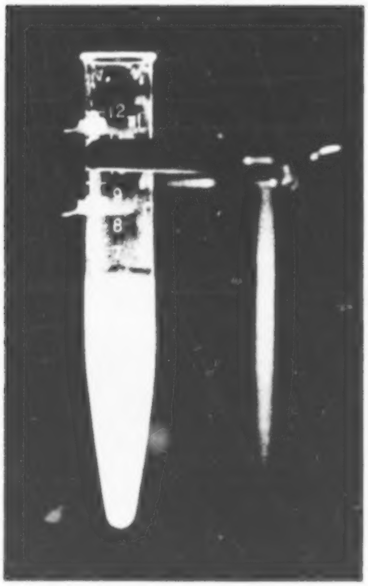
SG 24.7

If the new nuclide denoted by $_{93}(?)^{239}$ were also to emit a β:

$$_{93}(?)^{239} \longrightarrow {}_{94}(?)^{239} + {}_{-1}e^0 + \bar{\nu}\ .$$

In this way, two new elements might be produced (with Z = 93 and 94). If these reactions could be made to occur, the result would be the man-made production of an element, or elements, not previously known to exist—transuranium elements.

Fermi found in 1934 that the bombardment of uranium with neutrons actually produced several new half-lives in the target; these were attributed to traces of new-formed transuranium elements.



By bombarding heavy elements with a variety of particles it has been possible to create artificially a series of transuranium elements. Those elements, up to Z = 103, are listed below. A tiny sample of one of them, curium 244—dissolved in a test tube of water, is shown in the 5-minute exposure above.

${}_{92}\text{U}$	Uranium
${}_{93}\text{Np}$	Neptunium
${}_{94}\text{Pu}$	Plutonium
${}_{95}\text{Am}$	Americium
${}_{96}\text{Cm}$	Curium
${}_{97}\text{Bk}$	Berkelium
${}_{98}\text{Cf}$	Californium
${}_{99}\text{Es}$	Einsteinium
${}_{100}\text{Fm}$	Fermium
${}_{101}\text{Md}$	Mendelevium
${}_{102}\text{No}$	Nobelium
${}_{103}\text{Lw}$	Lawrencium

The results aroused much interest, and in the next five years a number of workers experimented with the neutron bombardment of uranium. Many different radioactive half-lives were discovered, but attempts to identify these half-lives with particular elements led to great confusion. The methods used were similar to those used in the study of the natural radioactive elements. A radioactive nuclide formed in a nuclear reaction is usually present in the target area only in an extremely small amount, possibly as little as 10^{-12} grams, and special techniques to separate these small quantities had to be developed.

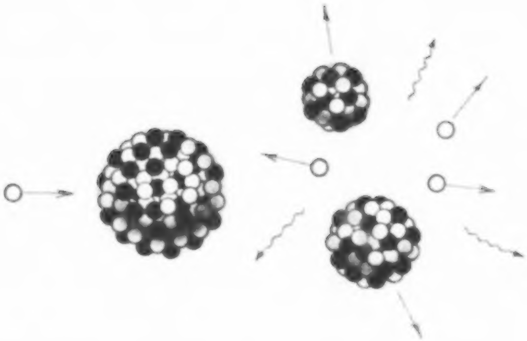
The reason for the confusion was found early in 1939 when Otto Hahn and Fritz Strassmann, two German chemists, showed definitely that one of the supposed transuranium elements was actually an isotope of barium (${}_{56}\text{Ba}^{139}$), identified by its half-life of 86 minutes and its chemical behavior. Another nuclide resulting from the neutron bombardment of uranium was identified as lanthanum (${}_{57}\text{La}^{140}$) with a half-life of 40 hours.

The production of the nuclides ${}_{56}\text{Ba}^{139}$ and ${}_{57}\text{La}^{140}$ from uranium, which has the atomic number 92 and an atomic mass of nearly 240, required an unknown kind of nuclear reaction in which the uranium nucleus is split almost in half. If such a process really occurred, it should also be possible to find "the other half," that is, to find nuclides with mass between 90 and 100 and atomic numbers of about 35. Hahn and Strassmann were able to find a radioactive isotope of strontium ($Z = 38$) and one of yttrium ($Z = 39$) which fulfilled these conditions, as well as isotopes of krypton ($Z = 36$) and xenon ($Z = 54$). It was clear from the chemical evidence that the uranium nucleus, when bombarded with neutrons, can indeed split into two nuclei of intermediate atomic mass.

Although Hahn and Strassmann showed that isotopes of intermediate mass did appear, they hesitated to state the conclusion that the uranium nucleus could be split into two large parts. In their report dated January 9, 1939, they said:

> On the basis of these briefly presented experiments, we must, as chemists, really rename the previously offered scheme and set the symbols Ba, La, Ce in place of Ra, Ac, Th. As "nuclear chemists" with close ties to physics, we cannot decide to make a step so contrary to all existing experience of nuclear physics. After all, a series of strange coincidences may, perhaps, have led to these results.

The step which Hahn and Strassmann could not bring themselves to take was taken on January 16, 1939 by two Austrian physicists, Miss Lise Meitner and Otto R. Frisch. They



Schematic diagram representing uranium fission.

suggested that the neutron initiated a decomposition of the uranium nucleus into "two nuclei of roughly equal size," a process which they called "nuclear fission" after the division, or fission, of a living cell into two parts. They predicted that the fragments would have great kinetic energy and would be radioactive. The predictions of Meitner and Frisch were soon verified experimentally. Shortly afterward, it was found that transuranium elements also are formed when uranium is bombarded with neutrons. In other words the capture of a neutron by uranium sometimes leads to fission, and sometimes leads to β decay. The β decay results in the formation of isotopes of elements of atomic number 93 and 94—later named neptunium and plutonium. The mixture of the two types of reaction, fission and neutron capture, followed by β decay, was responsible for the difficulty and confusion in the analysis of the effects of bombarding uranium with neutrons. The experiments opened two new fields of scientific endeavor: the physics and chemistry of the transuranium elements and the study and use of nuclear fission.

Lise Meitner and Otto Hahn

Lise Meitner, born in Austria, joined Otto Hahn in 1908 in a research collaboration that lasted thirty years. In 1938, Miss Meitner was forced to leave Germany. She was in Sweden when she published the first report on fission with her nephew, O. R. Frisch.

The discovery of nuclear fission inspired research workers all over the world and much new information was obtained within a short time. It was found that a uranium nucleus, after capturing a neutron, can split into one of more than 40 different pairs of fragments. Radiochemical analysis showed that nuclides result with atomic numbers from 30 to 63 and with mass numbers from 72 to 158. Neutrons also are emitted in fission; the average number of neutrons emitted is usually between 2 and 3. (Under appropriate conditions these neutrons can, in turn, cause fission in neighboring uranium atoms, and a process known as a chain reaction can develop in a sample of uranium.) The following reaction indicates one of the many ways in which a uranium nucleus can split:

$$ {}_0n^1 + {}_{92}U^{235} \longrightarrow {}_{56}Ba^{141} + {}_{36}Kr^{92} + 3\ {}_0n^1 \ . $$

Otto Frisch

SG 24.8

SG 24.9

The nuclides $_{56}Ba^{141}$ and $_{36}Kr^{92}$ are not found in nature and are not stable; they are radioactive and decay by β emission. For example, $_{56}Ba^{141}$ can decay into $_{59}Pr^{141}$ by successive emission of three β particles, as shown by the following scheme (in which the numbers in parentheses are the half-lives):

$$_{56}Ba^{141} \xrightarrow[\text{(18 min)}]{\;_{-1}e^{0}\;} {}_{57}La^{141} \xrightarrow[\text{(3.6 hr)}]{\;_{-1}e^{0}\;} {}_{58}Ce^{141} \xrightarrow[\text{(32 days)}]{\;_{-1}e^{0}\;} {}_{59}Pr^{141}$$

Similarly, $_{36}Kr^{92}$ is transformed into $_{40}Zr^{92}$ by four successive β decays.

Only certain nuclides can undergo fission. For those which can, the probability that a nucleus will split depends on the energy of the neutrons used in the bombardment. The nuclides $_{92}U^{235}$ and $_{94}Pu^{239}$ can undergo fission when bombarded with neutrons of any energy, from a small fraction of an electron volt, say 0.01 eV or less, up. On the other hand, U^{238} and Th^{232} undergo fission only when bombarded with neutrons having kinetic energies of 1 MeV or more. The latter nuclides, which have even Z and even A, are less likely to undergo fission than are uranium 235 and plutonium 230 which have even Z and odd A. Such information is very helpful in trying to construct the nuclear models to be discussed in Sec. 24.11, 12.

Plutonium 239 ($_{94}Pu^{239}$) is produced by the capture of a neutron by $_{92}U^{238}$ and the subsequent emission of two β particles, as discussed on p. 89.

The energy released in the fission reaction is about 200 MeV. This value can be calculated either directly from the atomic masses or from the average binding energy curve of Fig. 24.1b. The energy release is much larger than in the more common nuclear reactions (usually less than 10 MeV). The combination of the large energy release in fission and the possibility of a chain reaction is the basis of the large-scale use of nuclear energy.

Q5 What two reactions resulted in the appearance of a transuranium element?

Q6 What product of fission makes a chain reaction possible?

Summary 24.6
1. Control of a fission reaction depends on the balance between neutron production and loss.

2. Moderators are used for reducing the energy of the fast neutrons; slow neutrons have a greater probability of promoting fission.

3. Light nuclei absorb energy from neutrons in fewer collisions than do heavy nuclei, and so make good moderators.

4. Control of a chain reaction also usually involves a material whose nuclei absorb neutrons.

F54: Fission

24.6 Nuclear fission: controlling chain reactions.

For a chain reaction to continue at a constant level, it is necessary that there be a favorable balance between the net production of neutrons by fissions and the loss of neutrons due to the following three processes:

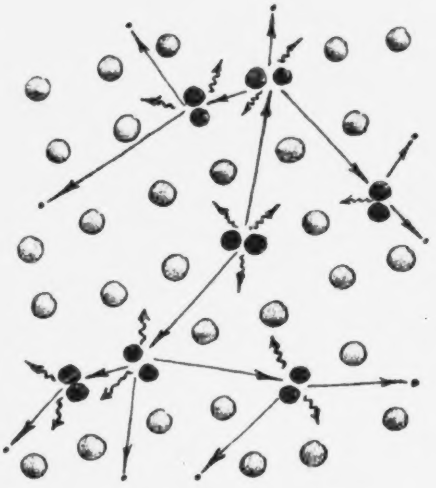
(1) capture of neutrons by uranium not resulting in fissions;

(2) capture of neutrons by other materials;

(3) escape of neutrons without being captured.

√

If too many neutrons escape or are absorbed, there will not be enough to sustain the chain reaction. If too few neutrons escape or are absorbed, the reaction will build up. The design of nuclear reactors as energy sources involves finding proper sizes, shapes, and materials to maintain a balance between neutron production and loss.



A schematic diagram of the beginning of a chain reaction. The nucleus in the center has fissioned into 2 parts, releasing gamma rays and neutrons. Some of the neutrons are captured by other nuclei, promoting further fissioning with the accompanying release of more neutrons.... and so on.

Since the nucleus occupies only a tiny fraction of an atom's volume, the chance of a neutron's colliding with a uranium nucleus is small and a neutron can pass through billions of uranium (or other) atoms while moving a few inches. If the assembly is small, a significant percentage of the fission neutrons can escape from the assembly without causing further fissions. The leakage of neutrons can be so large that a chain reaction cannot be sustained. If the assembly is made larger, a smaller percentage of the neutrons escape, or leak out: if the assembly were infinitely large, this fraction would approach zero. For a given combination of materials—uranium and other materials which may be needed—there is a size, called the critical size, for which the net production of neutrons by fission is just equal to the loss of neutrons by nonfission capture and leakage. If the size of the assembly is smaller than this critical size, a chain reaction cannot be sustained. The determination of the materials and their arrangement with which a reasonable critical size can be obtained is an important part of research in the new field of "nuclear engineering."

SG 24.10

L6-5 : Critical size

Another important problem in the design of nuclear reactors arises from the fact that fission is much more probable when U^{235} is bombarded with slow neutrons than when it is bombarded with fast neutrons. Although nuclear reactors can be built in which the fissions are induced by fast neutrons, it has been easier to build reactors in which the fissions are induced by slow neutrons. The neutrons released in fission have kinetic energies from about 0.01 MeV to nearly 20 MeV, with an average kinetic energy of about 2 MeV. The fast fission neutrons can be slowed down if the uranium is mixed with a material to which the neutrons can lose energy in collisions. The material should be relatively low in atomic mass so that the neutrons can transfer a significant fraction of their energy in elastic collisions; but the material should not absorb many neutrons. Carbon in the form of graphite, and also water, heavy water and beryllium meet these requirements. These substances are called moderators because they slow down—moderate—the newly produced neutrons to energies at which the probability of causing additional fission is high.

Other terms also are used in this connection. For a given shape, e.g. a sphere, there will be a critical mass, and for a given mass there will be a critical geometry (involving shape and/or the position of several components). SG 24.10 brings these issues up.

See "Success" in Project Physics Reader 6.

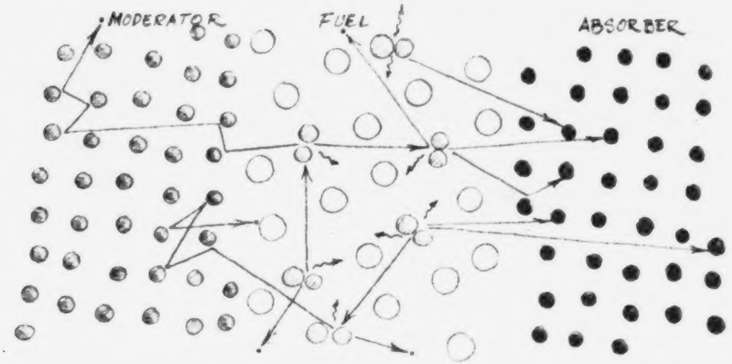


Fig. 24.2 Schematic diagram of processes in a nuclear reactor.

Hydrogen atoms in water are very effective in slowing down neutrons because the mass of a hydrogen nucleus is nearly the same as that of a neutron and because the number of hydrogen atoms per unit volume is high. A neutron can lose a large fraction of its energy in a collision with a hydrogen nucleus and only about 15 to 20 collisions are needed, on the average, to slow down the neutron to energies of 1 eV or less. However, the use of hydrogen has the disadvantage that the probability of the reaction

$${}_1H^1 + {}_0n^1 \longrightarrow {}_1H^2 + \gamma$$

is large enough so that too many neutrons may be absorbed by the hydrogen. In fact, it has been found impossible to achieve a chain reaction with natural uranium and water.

Heavy water: $(H^2)_2O$, or D_2O.

On the other hand, the absorption of a neutron by a deuterium nucleus in heavy water

$${}_1H^2 + {}_0n^1 \longrightarrow {}_1H^3 + \gamma$$

has an extremely small probability. A chain reaction can therefore be achieved easily with natural uranium and heavy water. Reactors with natural uranium as the fuel and heavy water as the moderator have been built in the United States, Canada, France, Sweden, Norway and other countries.

The contrast between the nuclear properties of hydrogen and deuterium has important implications for the development of nuclear reactors. Heavy water (D_2O) is much more expensive than ordinary water (H_2O) but, when it is used with natural uranium (mostly U^{238}) a chain reaction can be achieved efficiently. Ordinary water can be used, nonetheless, if uranium enriched in the isotope U^{235} is used instead of natural uranium. Many reactors "fueled" with enriched uranium and with ordinary water have been built in the United States. In fact, this general reactor type has been used in nearly all the large nuclear power plants built so far and in the reactors used in nuclear-powered submarines.

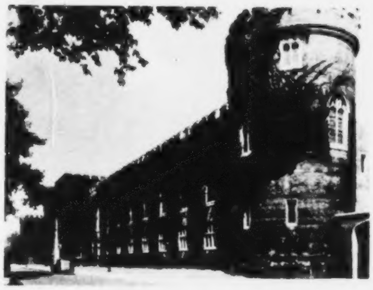
Carbon in the form of graphite has been used as a moderator in many reactors, including the earliest ones. It is not as good a slowing-down agent as water or heavy water: about 120 collisions with carbon atoms are needed to slow fission neutrons with an average energy of 2 MeV to the energy of about 0.025 eV desired; in heavy water only about 25 collisions are needed, and in water about 15. Although carbon in the form of graphite is not the best moderator and absorbs some neutrons, it does permit a chain reaction to occur when lumps of natural uranium (cylindrical rods, for example) are suitably arranged in a large mass of graphite. The rods must be of appropriate size and must be suitably spaced throughout the graphite. The determination of just how this could be done was one of the main problems that had to be solved before the first chain reaction could be achieved, in 1942 at the University of Chicago. Many graphite-moderated reactors are now in operation throughout the world.

The control of a reactor is relatively simple. If fission is occurring too frequently a few "control" rods are inserted into the reactor. The rods consist of a material (such as cadmium or boron) that absorbs slow neutrons, thereby reducing the number of neutrons in the moderator. Removal of the control rods will allow the reaction to speed up. Fig. 24.2 is a schematic diagram of the main processes that occur in a nuclear reactor in which uranium is the fissionable material.

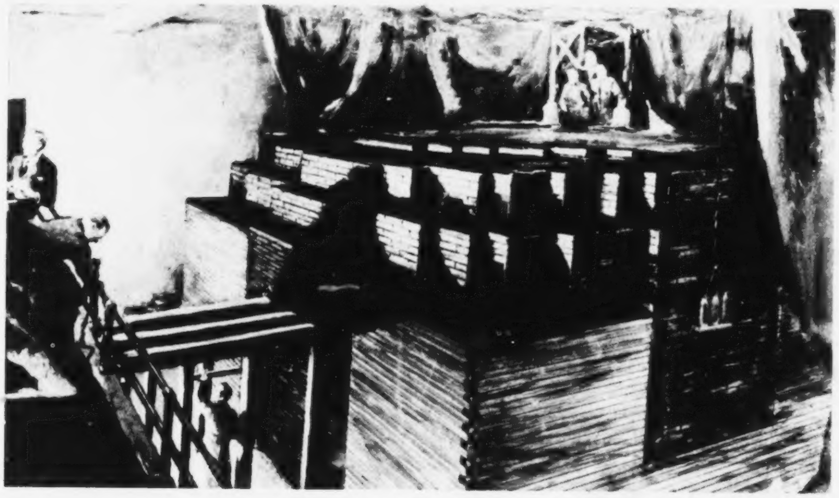
Q7 What is a "moderator?"

Q8 What is an advantage and a disadvantage of using water as a moderator in nuclear reactors?

ON DECEMBER 2, 1942
MAN ACHIEVED HERE
THE FIRST SELF-SUSTAINING CHAIN REACTIO
AND THEREBY INITIATED THE
CONTROLLED RELEASE OF NUCLEAR ENERGY



The west wall of the football stands of Stagg Field. Squash courts under these stands were used as the construction site of the first nuclear reactor. Below is an artist's sketch of that graphite-moderated reactor as it first became self-sustaining.



24.7 Nuclear fission: large-scale energy release and some of its consequences. The large-scale use of nuclear energy in chain reactions was accomplished in the United States between 1939 and 1945. The work was done under the pressure of World War II, as a result of the cooperative efforts of large numbers of scientists and engineers. The workers in the U.S. included Americans, Britons and European refugees from fascist-controlled countries. The energy was used in two forms: in the so-called atomic bomb, in which an extensive chain reaction occurs in a few millionths of a second; and in the nuclear reactor, in which the operating conditions are so arranged that the energy from fission is released at a much slower and steadier rate. In the nuclear reactor the fissionable material is mixed with other materials in such a way that, on the average, only one of the neutrons emitted in fission causes the fission of another nucleus; in this way the chain reaction just sustains itself. In a nuclear bomb the fissionable material is unmixed (that is, pure) and the device is designed so that nearly all of the neutrons emitted in each fission cause fissions in other nuclei.

It was essentially an applied engineering problem rather than a research problem in physics. Analogous work was known to be in progress in Nazi Germany

Summary 24.7

1. Nuclear energy can be released quickly, as in the atomic bomb, or slowly, as in a nuclear reactor.

2. Nuclear explosions, terrible as they are in blast alone, are made even more destructive by the "fall out" of radioactive debris.

3. The use of controlled fission as a source of heat energy has led finally to practical commercial power stations.

4. Vital problems concerning the use of nuclear energy require a well informed citizenry.

Nuclear reactors were used during World War II to manufacture Pu^{239} from U^{238}. They were designed in such a way that some of the neutrons from the fission of U^{235} were slowed down enough so that they would not cause fission of U^{238} but, instead, were absorbed by the U^{238} to form Pu^{239} through the reactions described in the previous section. A single nuclear bomb, using U^{235}, destroyed the city of Hiroshima, Japan, on August 6, 1945; another bomb, using $_{94}Pu^{239}$, destroyed the city of Nagasaki three days later, just prior to the surrender of Japan and the end of World War II.

Since the end of World War II in 1945, the use of nuclear energy from fission has been developed in two different directions. One direction has been military. Other countries besides the United States have made nuclear weapons, namely, the United Kingdom, the Soviet Union, France, and China. The enormous death-dealing capability of these weapons and the ever-larger numbers of bombs that have been accumulating have increased and made more dangerous the tension throughout the world and have emphasized the need for the peaceful settlement of international disputes.

Scientists have been prominently involved in activities to alert their government and fellow citizens to the moral and practical problems raised by the nuclear weapons race.

One incidental problem has been that of the radioactive fallout from bomb tests. The explosion of a nuclear bomb liberates very large amounts of radioactive materials. These materials can be blown by winds from one part of the world to another and carried down from the atmosphere by rain or snow. Some of the radioactivities are long-lived; the materials may be absorbed in growing foodstuffs and eaten by animals and people. It is known that under certain conditions radioactive materials can cause harmful genetic effects as well as somatic effects. One of the most abundant and long-lived products of the fission of U^{235} and Pu^{239} is strontium 90 ($_{38}Sr^{90}$). This isotope of strontium is similar to $_{20}Ca^{40}$ in its chemical properties. Hence when Sr^{90} is taken into the body, it finds its way into bone material. It decays by emission of 0.54-MeV β particles (half-life = 28 years). If present in large quantities it can cause leukemia, bone tumor, and possibly other forms of damage, particularly in growing children. There has been much research and discussion of the possibility of damage to present and future generations. As a result, the United States, the United Kingdom, the Soviet Union and most other nations agreed, in 1963, to a moratorium on further bomb tests in the atmosphere.

A technician checking milk samples for radioactivity.

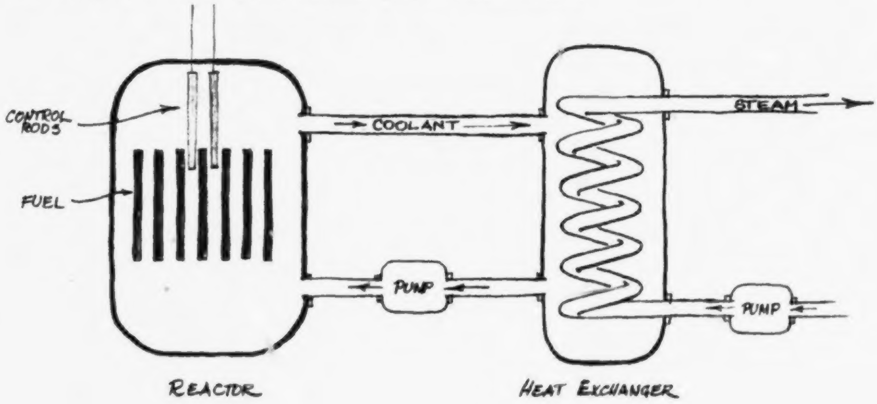
Genetic effects of radiation: effects producing changes in cells which will affect offspring of exposed individual.

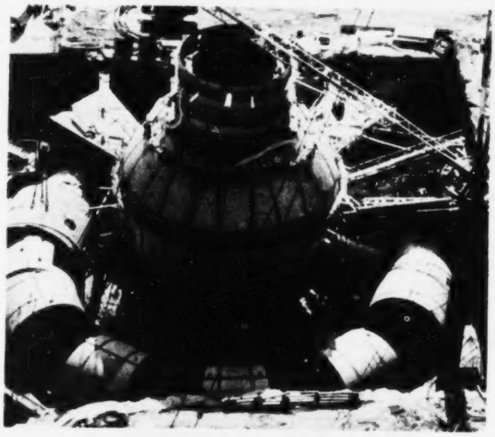
Somatic effects: all effects caused by radiation to an individual during his lifetime.

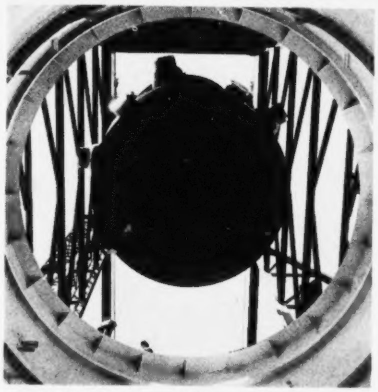
The second direction in which the use of nuclear energy has been pushed on a large scale has been in the production of electrical power from the energy released in fission. The increasing need for electrical energy is an important aspect of modern life. The amount of electricity used in an advanced industrial country, such as the United States, has been doubling approximately every ten years since about 1900. Although there are still large supplies of coal, oil and natural gas, it is evident that additional sources of energy will be needed, and nuclear energy from fission can fill this need.

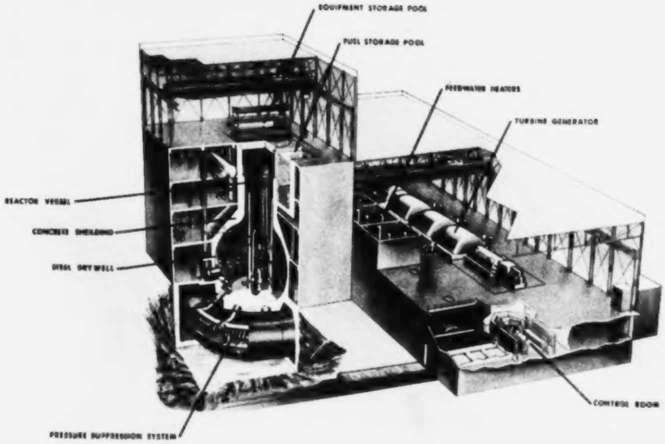
See "The Nuclear Energy Revolution" in Project Physics Reader 6.

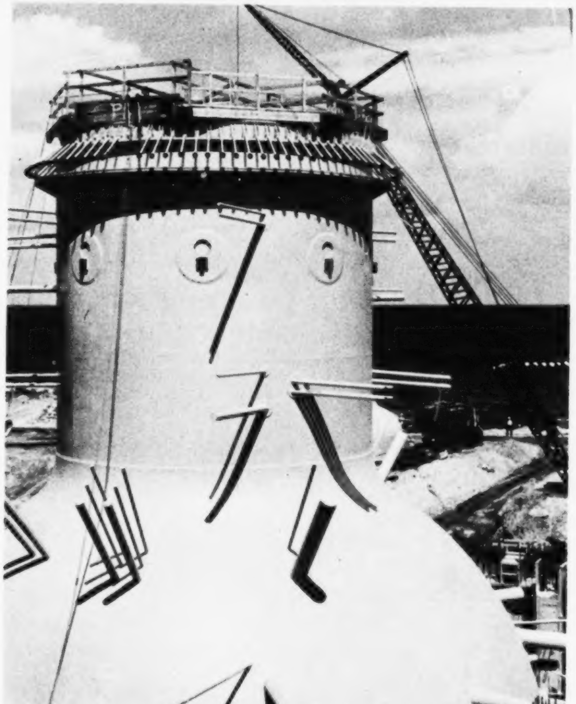
In almost all present systems of nuclear power production, the reactor is a source of heat for running steam turbines; the turbines drive electrical generators just as they do in conventional power stations.



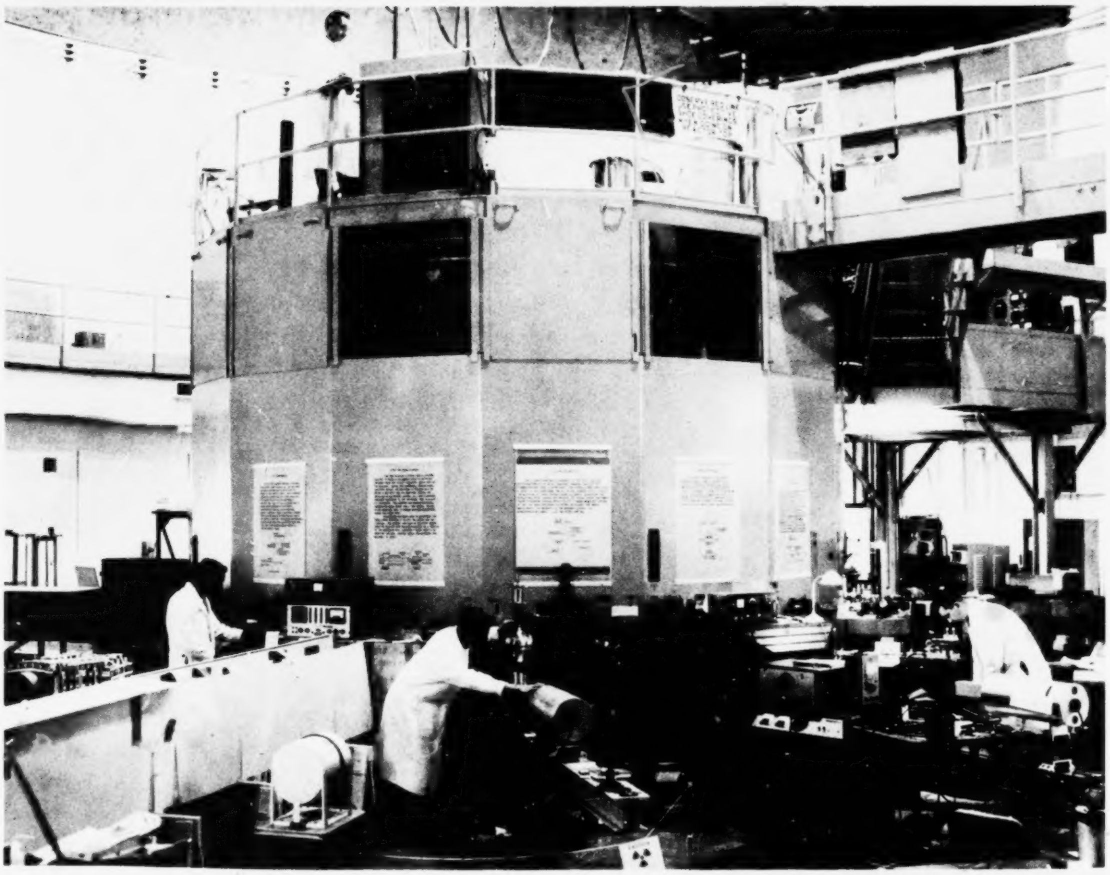


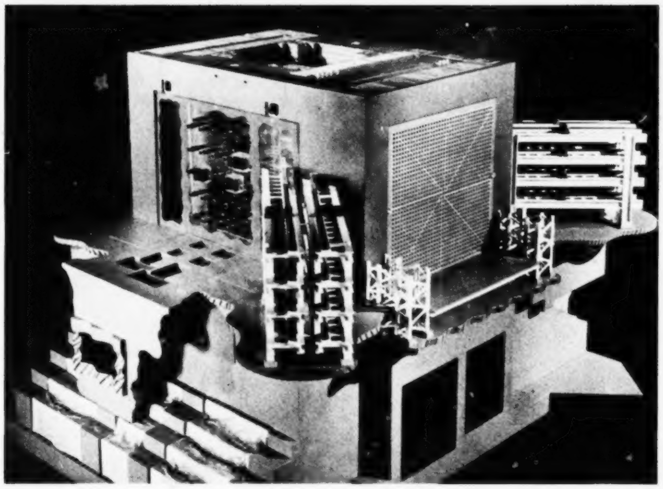


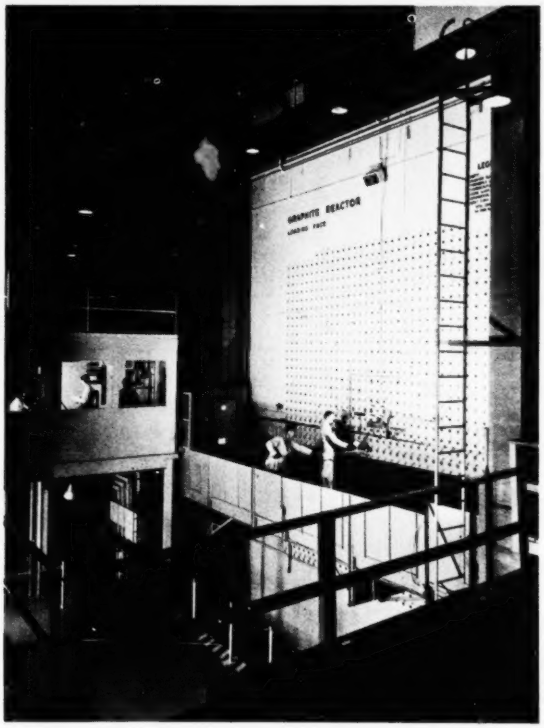

EQUIPMENT STORAGE POOL
FUEL STORAGE POOL
FEEDWATER HEATERS
TURBINE GENERATOR
REACTOR VESSEL
CONCRETE SHIELDING
STEEL DRYWELL
CONTROL ROOM
PRESSURE SUPPRESSION SYSTEM



These photographs illustrate one type of commercial installation for converting the heat energy from a fusion chain reaction into electrical energy. The steel "drywell" at the left is the housing for the nuclear reactor at the Nine Mile Point generating station, near Oswego on Lake Ontario. Just above, the reactor vessel is shown being lowered into the drywell. A later stage of construction is shown at the top. The cutaway drawing shows the reactor, turbine-generator and other components of a similar installation: the Dresden nuclear power station at Joliet, Illinois.







The photos on this page show 3 research reactors.

At the top is the small research reactor at M.I.T. in Cambridge, Mass.

At the right, technicians load fuel slugs in the A.E.C.'s graphite reactor at Oak Ridge, Tennessee.

Above is a model of the Brookhaven graphite reactor.

24.7

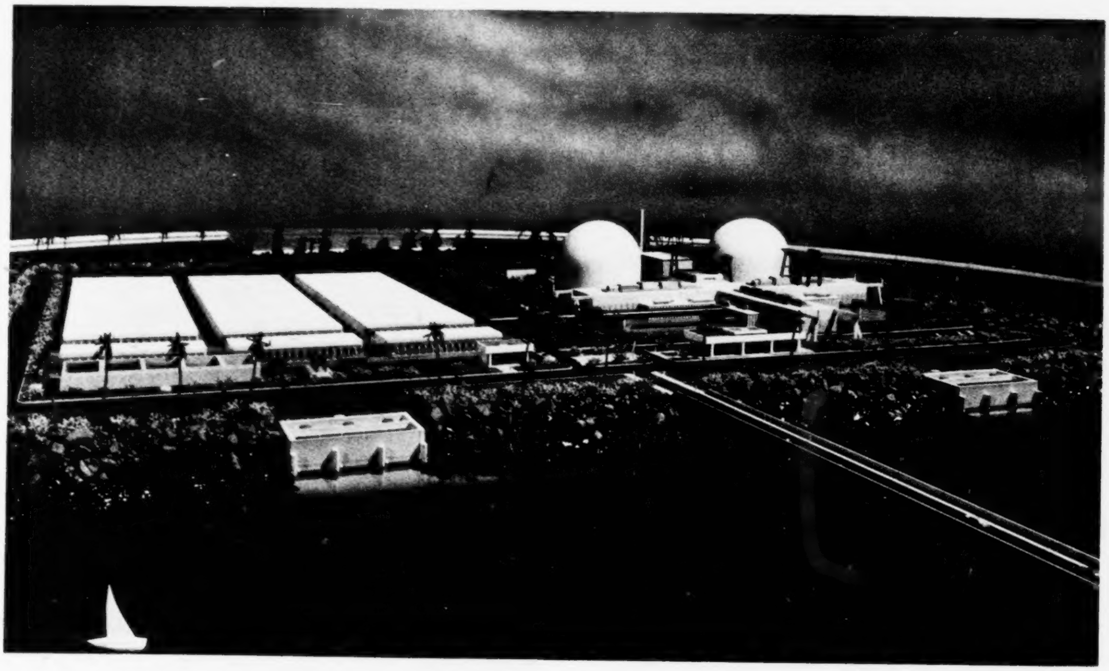
See "A Report to the Secretary of War," "Twentieth Birthday of the Atomic Age" and "Calling All Stars" in Project Physics Reader 6.

For a variety of reasons, some administrative and some technical, but mostly connected with the "Cold War" that started after World War II and intensified during the early fifties, the U. S. Atomic Energy Commission (AEC) did not emphasize applied research on nuclear-electric power systems until President Eisenhower so directed in 1953. By that time America's first experimental breeder reactor (EBR-1) had demonstrated for two years in Idaho that electric power could be produced in significant amounts while simultaneously producing plutonium from the U^{238} blanket around the neutron-and energy-producing core.

Not until fully twenty years after the Manhattan Project reached its goals could one say that the age of nuclear-electric generation of power had arrived. Nuclear energy sources became economically competitive with hydroelectric and fossil-fuel sources in the early 1960's when costs per kilowatt-hour were reduced to as low as one-half cent. In 1966 there were 29 contracts for construction of large nuclear power reactors in the United States alone. This commitment represented more than half of the total new power plant construction in the United States. The British and French also successfully used reactors to generate commercial electric power. Thus there finally are strong reasons for optimism concerning new sources of energy.

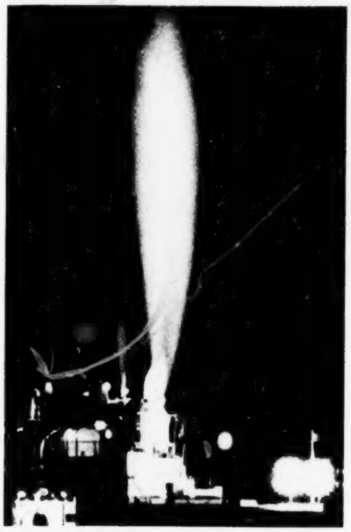
Below is shown a model of a nuclear power and desalting plant to be built on a man-made island off the coast of southern California. It will generate electricity at the rate of 1.8 million kilowatts and also produce, by distillation, 150 million gallons of fresh water daily.

Such new sources were clearly needed, for along with the population explosion, the depletion of fossil fuels and the falling water table, an energy shortage threatened

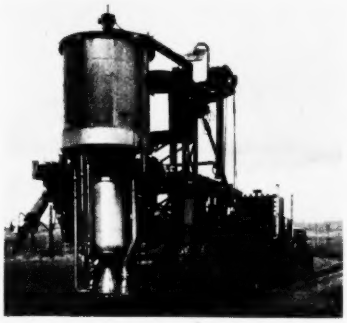


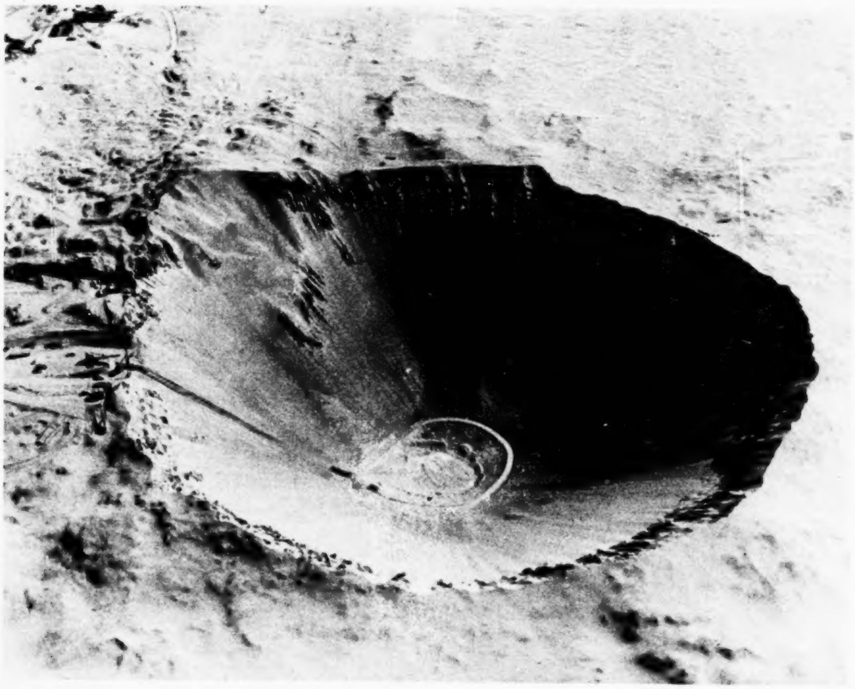
to limit mankind's future development. Power reactors, now entering a third generation of development, show definite promise of being able to desalt sea water economically, to convert atmospheric nitrogen into powdered fertilizers, and to make fluid fuels from hydrocarbons in low-grade coal. If all this can be done cheaply enough with breeder reactors that produce at least as much fissionable material as they "burn," then indeed the war-born nuclear technology at last can have the beneficial impact on all of human society that is so desperately needed.

In the meantime, the social costs of the nuclear energy revolution have already been very high—in human lives, in money, and in the anxiety of life under the threat of nuclear war. In some ways these are analogous problems to the human price of industrialization after the development of the steam engine (Unit 3). At the same time, the potential benefit to man is great. As in the past, the decisions that will be necessary in the future development of nuclear power cannot be made on the basis of physics alone. Science can illuminate alternatives, but it cannot and should not be used by itself to choose among them. Responsible scientific opinion must be supplemented by political insight and a broad humanistic view of society. But at the very least, responsible citizens must have some understanding of the scientific principles that will underlie the alternatives among which they must choose.



A blast of hydrogen exhaust (above) from an experimental nuclear rocket engine (below).





Among the many problems for public policy raised by developments in nuclear power is the Plowshare program of the A.E.C. The crater at the left was part of Plowshare's research into creating lakes, harbors and sea-level canals between oceans by the use of thermonuclear explosions.

Chronology of Developments in Nuclear Science and Technology

1896	Becquerel discovers unstable (radioactive) atoms.
1899	Isolation of radium by Curies.
1905	Einstein announces equivalence of mass and energy.
1911	Rutherford discovers nucleus.
1919	Rutherford achieves transmutation of one stable chemical element (nitrogen) into another (oxygen).
1920-1925	Improved mass spectrographs show that changes in mass per nuclear particle accompanying transmutation account for energy released by nucleus.
1931	Lawrence and Livingston construct first cyclotron.
1932	Chadwick identifies neutrons.
1939	Evidence of uranium fission by Hahn and Strassmann, identification of fission products by Meitner and Frisch.
1940	Discovery of neptunium and plutonium (transuranium elements) at the University of California.
1942	Achievement of first self-sustaining nuclear reaction, University of Chicago.
1945	First test of an atomic device, at Alamagordo, New Mexico, followed by the dropping of atomic bombs on Hiroshima and Nagasaki, at the end of World War II.
1946	President Truman signs the bill creating the U.S. Atomic Energy Commission. First shipment of radioactive isotopes from Oak Ridge goes to hospital in St. Louis, Missouri.
1951	First significant amount of electricity (100 kilowatts) produced from atomic energy at testing station in Idaho.
1952	First detonation of a hydrogen bomb, Eniwetok Atoll, Pacific Ocean.
1953	President Eisenhower announces U.S. Atoms-for-Peace program and proposes establishment of an international atomic energy agency.
1954	First nuclear-powered submarine, Nautilus, commissioned.
1955	First United Nations International Conference on Peaceful Uses of Atomic Energy held in Geneva, Switzerland.
1956	First commercial power plant begins operation at Calder Hall, England.
1957	Shippingport Atomic Power Plant in Pennsylvania reaches full power of 60,000 kilowatts. International Atomic Energy Agency formally established.
1959	First nuclear-powered merchant ship, the Savannah, launched at Camden, New Jersey.
1961	A radioactive isotope-powered electric generator placed in orbit, the first use of nuclear power in space.
1962	Nuclear power plant in the Antarctic becomes operational
1963	President Kennedy ratifies the Limited Test Ban Treaty for the United States.
1964	President Johnson signs law permitting private ownership of certain nuclear materials.
1966	Beginning of the rapid development of nuclear power plants in the U.S.
1968	"Non-proliferation" agreement, signed by the United States, the Soviet Union and other countries, limiting the number of countries possessing nuclear weapons.

24.8 Nuclear fusion. Fusion reactions have been produced in the laboratory by bombarding appropriate targets with, for example, high-energy deuterons from a particle accelerator. In these reactions energy is liberated, as expected. Some typical examples of fusion reactions, together with the energy liberated in each reaction, are:

$$_1H^2 + {}_1H^2 \longrightarrow {}_1H^3 + {}_1H^1 + 4 \text{ MeV},$$

$$_1H^2 + {}_1H^2 \longrightarrow {}_2He^3 + {}_0n^1 + 3.3 \text{ MeV},$$

$$_1H^2 + {}_1H^3 \longrightarrow {}_2He^4 + {}_0n^1 + 17.6 \text{ MeV},$$

$$_1H^2 + {}_2He^3 \longrightarrow {}_2He^4 + {}_1H^1 + 18.3 \text{ MeV}.$$

Summary 24.8
The tremendous energy release that would result from the controlled fusion of tritium and deuterium nuclei has not yet been exploitable. The difficulty is to confine the extremely hot plasma required for fusion.

In the first of the above equations, one product nucleus is an isotope of hydrogen, called tritium, with mass number $A = 3$; it is radioactive with a half-life of about 12 years and it decays by beta emission into $_2He^3$, an isotope of helium. When a target containing tritium is bombarded with deuterons, $_2He^4$ can be formed, as in the third equation above, liberating 17.6 MeV of energy. Of this energy, 14.1 MeV appears as kinetic energy of the neutron and 3.5 MeV as kinetic energy of the α particle.

Although the energy liberated in a single fusion is less than in a single fission, the energy per unit mass is much greater. About 50 helium atoms are needed to equal the mass of 1 uranium atom; 50×17.6 MeV is 1040 MeV—compared to 200 MeV for a typical fission.

The fusion of tritium and deuterium offers the possibility of providing large sources of energy, for example, in electric power plants. Deuterium occurs in water with an abundance of about one part in seven thousand of H^1 and can be separated from the lighter isotope. One gallon of water contains about one-eighth of a gram of deuterium which can be separated at a cost of about 4 cents. If this amount of deuterium could be made to react with tritium under appropriate conditions, the energy output would be equivalent to that from about 300 gallons of gasoline. The total amount of deuterium in the oceans is estimated to be about 10^{17} kilograms, and its energy content would be about 10^{20} kilowatt-years. If deuterium and tritium could be used to produce energy, they would provide an enormous source of energy. There are, however, some difficult problems to be solved, and some of these will be discussed briefly.

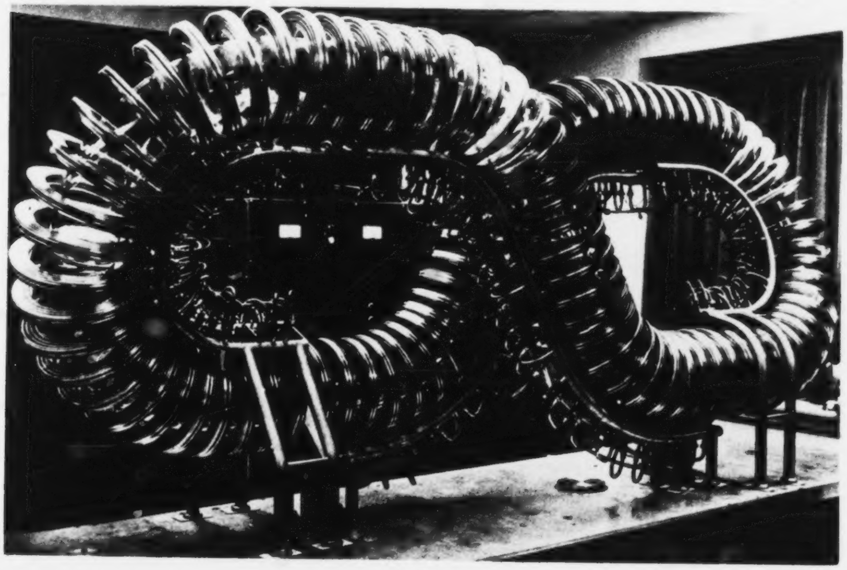
The nuclei which react in the fusion processes are positively charged and repel one another because of the repulsive electric force. The nuclei must, therefore, be made to collide with a high relative velocity to overcome the repulsive force tending to keep them apart. Experiments have shown that this can occur when the particles have kinetic energies of about 0.1 MeV or more. The nuclei must also be confined in a region where they can undergo many collisions without escaping, being absorbed by the walls bounding the region or losing energy by collisions with cooler molecules. There must be enough collisions per unit time so that fusion can occur at a rate that will yield more energy than that needed to cause the collisions. The combination of these requirements means that the nuclei must be contained at a temperature of the order of 100 million degrees.

Plasma: ionized gas in which positively and negatively charged particles move about freely.

At the temperatures required for fusion, the atoms have been stripped of their electrons, and the resulting nuclei and separated electrons are said to form a plasma. No wall made of ordinary material can contain a hot plasma at 10^8°K (the wall would be vaporized instantly!). But the charged particles of a plasma could, in theory, be contained in an appropriately designed magnetic field. The first problem to be solved, therefore, is to contain the plasma of deuterium and tritium nuclei in a magnetic field, while accelerating the nuclei by means of an electric field to the required kinetic energy (or temperature). The rate at which the fusion reactions occur must also be regulated so as to produce energy which can be converted to electrical energy. These problems have not yet been solved on a practical scale, but research on them is being carried on in many countries. There is considerable international cooperation in this research, including visits of research teams between the United States, Britain and the U.S.S.R. Although the effort and expense are great, the possible pay-off in terms of future power resources is enormous.

Q9 **Why are very high temperatures required to cause fusion reactions?**

Q10 **How could extremely hot gases be kept from contacting the wall of a container?**



A demonstration model of a "Stellarator." The figure-eight shape enables strong magnetic fields to contain a continuous plasma stream in which a controlled fusion reaction might occur.

24.9 Fusion reactions in stars. One of the most fascinating aspects of nuclear physics is the study of the sources of the energy of different types of stars. Let us take the sun as an example. In the sun the fusion process involves the production of a helium nucleus from four protons. The net results of the reactions can be written as:

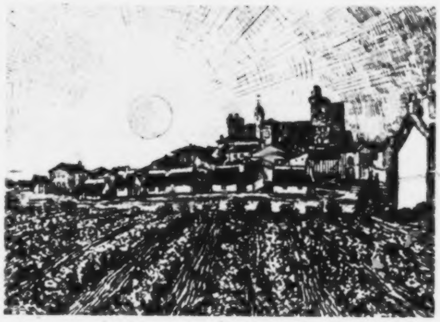
$$4\ {}_1H^1 \longrightarrow {}_2He^4 + 2\,{}_{+1}e^0 + 26 \text{ MeV.}$$

The reaction does not take place in a single step but can proceed through different paths of sets of reactions whose net results are summarized in the above equation; the amount of energy released is 26 MeV. The fusion of four protons into a helium nucleus is the main source of the energy of the sun. Chemical reactions cannot provide energy at large enough rates (or for long enough duration!) to account for energy production in the sun, but nuclear fusion reactions can. Hydrogen and helium together make up about 99 percent of the sun's mass, with approximately twice as much H as He, so there is plenty of hydrogen to supply the sun's energy for millions of years to come.

The possibility that four protons could collide to form a helium nucleus has been ruled out because the probability for such a reaction under solar conditions is too low to account for the amount of energy released. It now seems more likely that the four protons are formed into a helium nucleus in several steps, that is, by a series of nuclear reactions. We shall mention briefly one such series. When the temperature reaches about 10^7°K, the kinetic energies are large enough to overcome the electric repulsion between protons, and fusion of two protons (${}_1H^1$) takes place. The nuclear reaction results in a deuteron (${}_1H^2$), a positron (${}_{+1}e^0$) and a neutrino. As soon as a deuteron is formed, it reacts with another proton resulting in helium 3 (${}_2He^3$) and a γ ray. The helium 3 nuclei fuse with each other forming α particles and two protons. In each of these reactions energy is released, resulting in 26 MeV for the complete cycle of four protons forming a helium nucleus.

The rates of the reaction depend on the number of nuclei per unit volume and on the temperature; the higher the temperature, the faster the thermal motion of the particles and the more frequent and energetic the collisions. At the temperature of the sun's interior, which has been estimated to be 10 to 20 million degrees, the kinetic energies resulting from the thermal motion are in the neighborhood of 1 KeV.

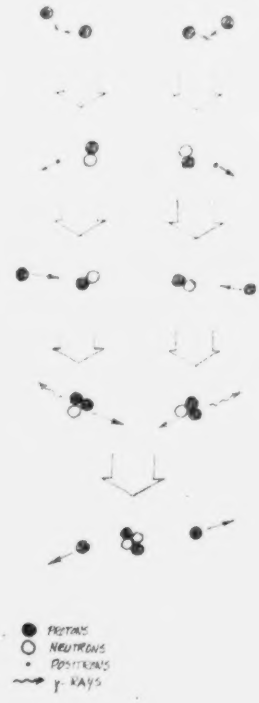
Man has been able to achieve the release of large amounts



Pen drawing by Vincent van Gogh

Summary 24.9
The extremely high temperatures of many stars enables the proton-proton reactions to occur, resulting in nuclear fusion. Thermonuclear explosions result when a fission reaction initiates a fusion reaction.

One form of proton-proton fusion chain which releases energy in stars:



See "Power from the Stars" in Project Physics Reader 6.

of energy by means of fusion processes in thermonuclear explosions, such as hydrogen bombs. A hydrogen bomb consists of a mixture of light elements with a fission bomb. The latter acts as a fuel that initiates the fusion of the light elements. The explosion of a fission bomb produces a temperature of about 5 × 10^{7}° K, which is sufficiently high to make fusion possible. The fusion reactions then release additional large amounts of energy. The total energy release is much greater than would be liberated by the fission bomb alone.

SG 24.11
SG 24.12
SG 24.13
SG 24.14
SG 24.15
SG 24.16

Q11 Is the ratio of the amount of hydrogen to the amount of helium in the sun increasing or decreasing?

24.10 The strength of nuclear forces. The large energies involved in nuclear reactions, a million or more times larger than the energies involved in chemical (molecular) reactions, indicate that the forces holding the nucleus together are very much stronger than the forces that hold molecules together. Another clue to the magnitude of nuclear forces is the density of a typical nucleus. The work of Rutherford and his colleagues on the scattering of α particles showed that atomic nuclei have radii in the neighborhood of 10^{-13} cm to 10^{-12} cm; this means that the volume of an atomic nucleus may be as small as 10^{-39} to 10^{-36} cm^3. Now, the mass of one of the lighter atoms is of the order of 10^{-24} gram, and this mass is almost all concentrated in the nucleus, with the result that the density of the nucleus may be as high as 10^{12} to 10^{14} grams per cubic centimeter. Densities of such magnitude are thousands of billions of times beyond the limits of our ordinary experience since the greatest densities of ordinary material are in the neighborhood of 20 grams per cubic centimeter (uranium, gold, lead). It is evident that the forces that hold the atomic nucleus together must be very different from any forces we have considered so far. The search for understanding of these forces is one of the most important problems of modern physics and one of the most difficult. Although a good deal has been learned about nuclear forces, the problem is far from solved.

Summary 24.10
The incredible density of the nucleus implies very strong attractive nuclear forces. Information concerning binding energies indicate that nuclear forces decrease very rapidly with distance, so rapidly that a nucleon only interacts with its closest neighbors.

Information about nuclear forces has been obtained in several ways. It is possible to deduce some of the properties of nuclear forces from the known properties of atomic nuclei, for example, from the binding energy curve of Fig. 24.1b. That curve shows that the average binding energy per particle in a nucleus has nearly the same value for all but the lightest nuclei—about 8 MeV. In other words, the total binding energy of a nucleus is nearly proportional to the number of particles in the nucleus. Now, if every particle in the nucleus were to interact with every other particle, the energy of the interactions and, therefore, the binding energy would be approximately proportional to the number of interacting pairs. Each of the particles would interact with all others. The binding energy calculated by assuming such interacting pairs is very different from the experimental results. To avoid this contradiction it is necessary to assume that a nuclear particle does not interact with all other nuclear particles but only with a limited number of them, that is, only with its nearest neighbors. For this to be the case the nuclear forces must have a short range. The nuclear forces must fall off very rapidly as the distance between two nucleons increases. This decrease must be more rapid than the $1/r^2$ decrease of the gravitational force between two particles or the $1/r^2$ decrease of the Coulomb electric force between two charges.

The presence of protons in the nucleus also tells us something about nuclear forces. Since there are only positively charged and neutral particles in the nucleus, the electric forces must be repulsive. Since the nucleus is very small—of the order of 10^{-12} cm in diameter—these forces must be enormous. So why is the nucleus stable? It seems reasonable to assume that the electric repulsion is overcome at very small distances by very strong attractive forces between the nuclear particles. Information about such specifically nuclear forces can be obtained by studying the scattering of protons or neutrons by materials containing protons. Scattering experiments and the theory needed to account for their results form an important branch of nuclear physics. They show that such attractive nuclear forces do indeed exist, and many of the properties of these forces are now known—but not all. The complete solution of the problem of nuclear forces and how they hold the nucleus together has not yet been obtained; this problem lies at the frontier of nuclear research.

In the absence of a complete theory of nuclear forces and structure, models of the nucleus have been developed. Several models are used because no one model adequately describes the wide variety of nuclear phenomena, ranging from particle emission in radioactive decay to nuclear reactions and fission. Two of these models are of special interest: the liquid drop model and the shell model.

Q12 Why was it assumed that there are special nuclear forces to hold the nucleus together?

Q13 Why was it assumed that the nuclear force is very short-range?

See "Models of the Nucleus" in Project Physics Reader 6.

Summary 24.11
Using the liquid-drop model of the nucleus, Bohr and Wheeler were able to account for nuclear fission; if a neutron of sufficient KE is absorbed by the nucleus, the nucleus is deformed and fission results.

24.11 The liquid-drop nuclear model. In the liquid drop model the nucleus is regarded as analogous to a charged drop of liquid. This model was suggested because the molecules in a liquid drop are held together by short-range forces, as are the nucleons in a nucleus. According to this model, the particles in the nucleus, like the molecules in a drop of liquid, are in continual random motion. In analogy with the evaporation of molecules from the surface of a liquid drop, a group of nuclear particles may pick up enough energy through chance collisions with other nucleons to overcome the attractive nuclear forces and escape from the nucleus; this process would correspond to spontaneous α emissions. This model has been especially useful in describing nuclear reactions: a particle may enter the nucleus from outside and impart enough additional kinetic energy to the protons and neutrons to permit the escape of a proton or a neutron, or a combination such as a deuteron or an α particle. A quantitative theory of nuclear reactions based on this idea has been developed.

The usefulness of the liquid drop model is also shown in its ability to account for fission. When a sample of U^{235} is bombarded with slow neutrons, that is, neutrons whose kinetic energy is very small, a U^{235} nucleus may capture a neutron to form a U^{236} nucleus. We can calculate the binding energy of the captured neutron:

mass of U^{235} nucleus = 235.04393 amu
mass of neutron = 1.00867
total mass of the separate parts = 236.05260
mass of U^{236} nucleus = 236.04573
change of mass (Δm) = 0.00687 amu
binding energy = $0.00687 \text{ amu} \times 931 \frac{\text{MeV}}{\text{amu}}$
= 6.4 MeV.

At that instant when the neutron is captured, the U^{236} nucleus formed has this additional energy, 6.4 MeV, which is called the "excitation energy due to the neutron capture." This energy is several MeV even though the kinetic energy of the neutron is so small, less than 1 eV, that it can be neglected.

What happens to the excited U^{236} nucleus? This problem was studied theoretically in 1939 by Niels Bohr, who had come to the U. S., and John A. Wheeler, an American physicist. They showed that, according to the liquid drop model, the U^{236} can act like a drop of mercury when "excited" by being given mechanical energy. The nucleus can be deformed into an elongated or dumbbell-like shape whose two (charged) parts may be beyond the range of the attractive nuclear forces. The electric force of repulsion between the two parts of the deformed nucleus can overcome the short-range attractive forces, causing the nucleus to split, that is to undergo fission, and causing the fragments to separate with high velocity. Each of the fragments will then quickly assume a spherical (or nearly spherical) form because within it the attractive nuclear forces again predominate. A schematic picture of a possible sequence of steps is shown in Fig. 24.3. Fission occurs less than one billionth (10^{-9}) of a second after the neutron is captured.

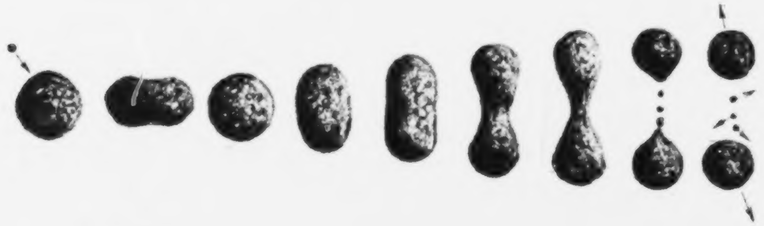


Fig. 24.3 Schematic representation of steps leading to the fission of a compound nucleus, according to the liquid drop model.

The liquid drop model gives a simple answer to the question: why do some nuclides (U^{235} and Pu^{239}) undergo fission with slow neutrons while others (Th^{232} and U^{238}) undergo fission only with fast neutrons? The answer is that a certain minimum amount of energy must be supplied to a nucleus to deform it enough so that the repulsive electric forces can overcome the attractive nuclear forces. This energy, called the activation energy, can be calculated with the aid of the mathematical theory of the liquid drop model. When U^{235} captures a neutron to make U^{236}, the excitation of the U^{236} nucleus is greater than the energy required for fission, even when the neutron has very low kinetic energy. This calculation was made by Bohr and Wheeler in 1939; they predicted, correctly, that U^{235} would undergo fission with slow neutrons. The theory also predicted that when U^{238} captures a slow neutron to form U^{239} the excitation energy is smaller than the activation energy by 0.9 MeV. Hence U^{238} should undergo fission only when bombarded with neutrons with kinetic energies of 0.9 MeV or more. The correctness of this prediction was verified by experiment.

When U^{235} captures a neutron to make U^{236}, the excitation of the U^{236} nucleus is greater than the energy required for fission, even when the neutron has very low kinetic energy.

SG 24.17

SG 24.18

Q14 According to the liquid drop model, what kind of force causes fission?

Q15 Why does U^{238} require *fast* neutrons to provoke fission?

Summary 24.12
The shell model was developed to account for nuclear properties unexplainable by the liquid-drop model. Using the Bohr-Rutherford electron shell configuration as an analogy, this model describes neutrons and protons as being in concentric shells. Each model has advantages and disadvantages and a collective model to combine the two is under development.

24.12 The shell model. Another nuclear model is required to account for other properties of the nucleus—properties that could not be accounted for by the liquid drop model. We saw in Sec. 22.7 that nuclides with even numbers of neutrons and protons are more stable than nuclides that contain odd numbers of either protons or neutrons. Detailed experimental studies of nuclear stability have shown that nuclei having 2, 8, 20, 50 or 82 protons, or 2, 8, 20, 50, 82 or 126 neutrons are unusually numerous and stable. These nuclei have greater binding energies than closely similar nuclei. When the exceptional properties of nuclei with these numbers of protons and neutrons became clear, in 1948, no available theory or model of the nucleus could account for this situation. The numbers 2, 8, 20, 50, 82 and 126 were referred to as "magic numbers."

It was known from the study of atomic properties that atoms with atomic numbers 2, 10, 18, 36, 54 and 86—the noble or inert gases helium to radon—also have special stability properties. These properties were explained in the Bohr-Rutherford model of the atom by the idea that the electrons around each nucleus tend to arrange themselves in concentric shells, with each shell able to contain only a certain maximum number of electrons: 2 for the innermost shell, 8 for the next, and so on. A full electron shell corresponds to an especially stable atom. Although the Bohr-Rutherford model has been replaced by quantum mechanics, the idea of shells still provides a useful picture, and a nuclear model—the nuclear shell model—has been developed.

As with the electron, the "shells" are thought of as quantized energy states.

In the nuclear shell model it is assumed that protons can, in a rough way of speaking, arrange themselves in shells, and that neutrons can, independently, do likewise; in the magic-number nuclei the shells are filled. The model has been worked out in great detail on the basis of quantum mechanics, and has been successful in correlating the properties of nuclides that emit α or β particles and γ photons, and in describing the electric and magnetic fields around nuclei. But the nuclear shell model does not help us understand fission, and there are fundamental differences between this model and the liquid-drop model. For example, the shell model emphasizes definite patterns in which nucleons are arranged, while the liquid-drop model pictures the nuclear material in random motion. Each model is successful in accounting for some nuclear phenomena but fails for others.

When two seemingly contradictory theories or models must be used in a field of physics, a strong effort is put into trying to develop a more general viewpoint, or theory, which can include the two as special cases. Such a nuclear theory is being developed; it is called the collective model, and one of the physicists who has worked on this model is Aage Bohr, the son of Niels Bohr. This model represents an advance beyond the shell and liquid-drop models in correlating nuclear data. It does not answer the fundamental question of the nature of nuclear forces, which is still one of the chief problems in the physics of our times.

Q16 According to the shell model, what makes the "magic numbers" of protons and neutrons magic?

Q17 Which is better, the liquid drop or the shell model?

24.13 Biological and medical applications of nuclear physics. In Sec. 24.7 we mentioned the military applications of nuclear energy and the use of nuclear energy as a source of electric power. There are many other applications which may, in the long run, turn out to be more important. These may be included under the general heading of radiation biology and medicine. The field of science indicated by this name is broad and we can only indicate, by means of a few examples, some of the problems that are being worked on. In this work, radiations are used in the study of biological phenomena, in the diagnosis and treatment of disease, and in the improvement of agriculture.

Summary 24.13
Nuclear reactors produce radioactive isotopes for use in many fields of research as well as in medical diagnosis and therapy.

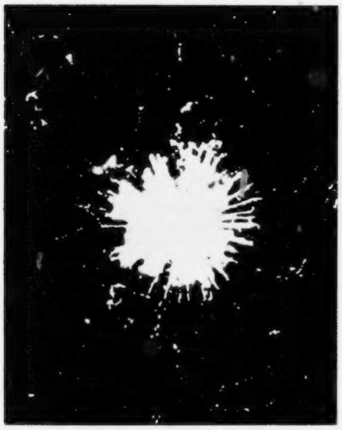
The physical and chemical effects of various kinds of radiations on biological materials are being studied to find out, for example, how radiation produces genetic changes. The metabolism of plants and animals is being studied with the aid of extremely small amounts of radioactive nuclides called isotopic tracers, or "tagged atoms." A radioactive isotope (for example, C^{14}) acts chemically and physiologically like a stable isotope (C^{12}). Hence a radioactive tracer can be followed with counters as they go through various metabolic processes. The ways in which these processes take place can be studied accurately and relatively easily by means of these techniques. The role of micronutrients (elements that are essential, in extremely small amounts, for the well-being of plants and animals) can be studied in this way. Agricultural experiments with fertilizers containing radioactive isotopes have shown at what point in the growth of a plant the fertilizer is essential. In chemistry, radioactive isotopes help in the determination of the details of chemical reactions and of the structure of complex molecules, such as proteins, vitamins and enzymes.

E48: Radioactive tracers

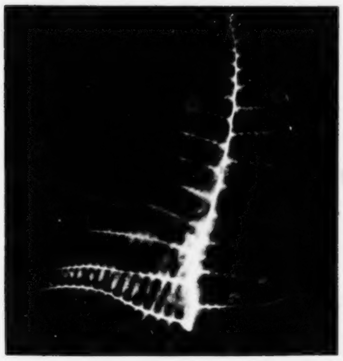
24.13

Table 24.1

Isotope	Half-life	Important Uses
$_1H^3$	11 years	Used as a tag in organic substances.
$_6C^{14}$	4700 years	Used as a tag in studying the synthesis of many organic substances. When $_6C^{14}$ is incorporated in food material, the metabolic products of the organism are marked with it.
$_{11}Na^{24}$	15 hours	Useful in a wide variety of biochemical investigations because of its solubility and chemical properties.
$_{15}P^{32}$	14 days	For the study of bone metabolism, the treatment of blood diseases and the specific uptake in tumor tissue.
$_{16}S^{35}$	87 days	Has numerous chemical and industrial applications.
$_{27}Co^{60}$	5.3 years	Because of its intense γ emission, may be used as a low-cost substitute for radium in radiography and therapy.
$_{53}I^{131}$	8 days	For the study of thyroid metabolism and the treatment of thyroid diseases.



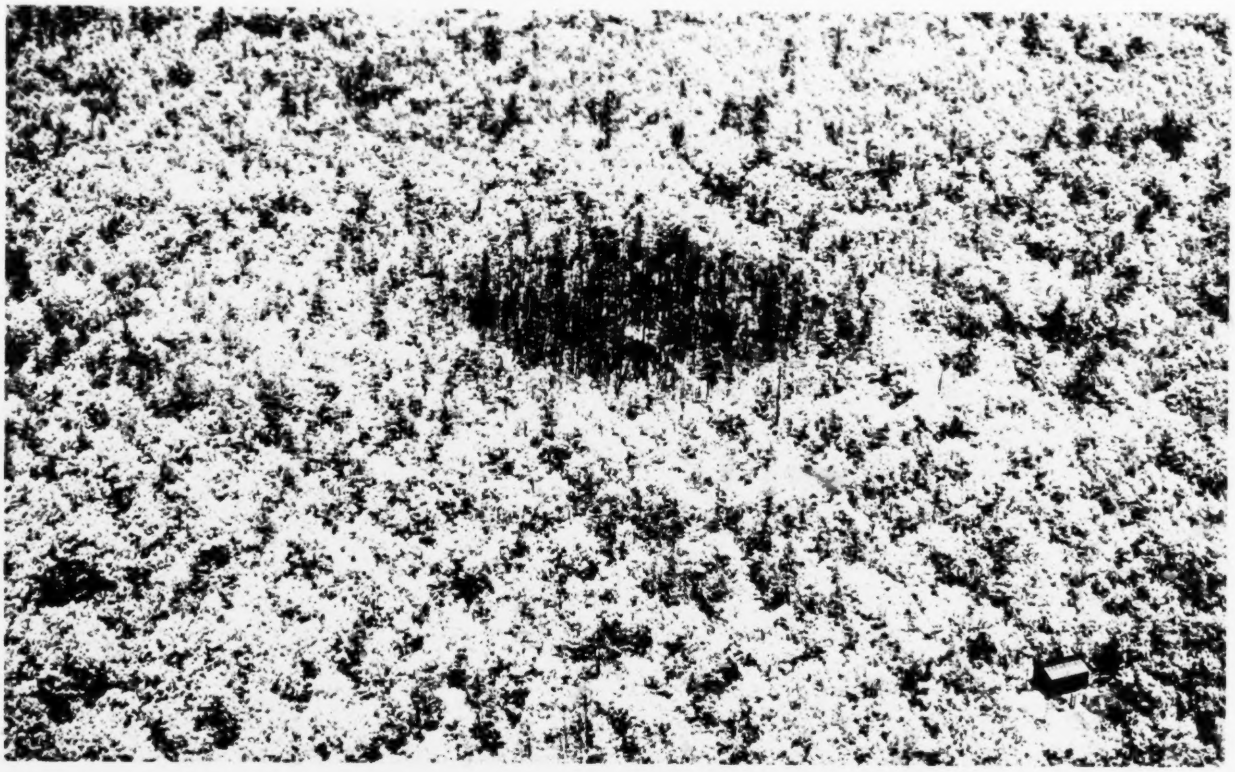
A grain of radioactive dust in the atmosphere is the origin of these α-particle tracks in a photographic emulsion (enlarged 2000 times).

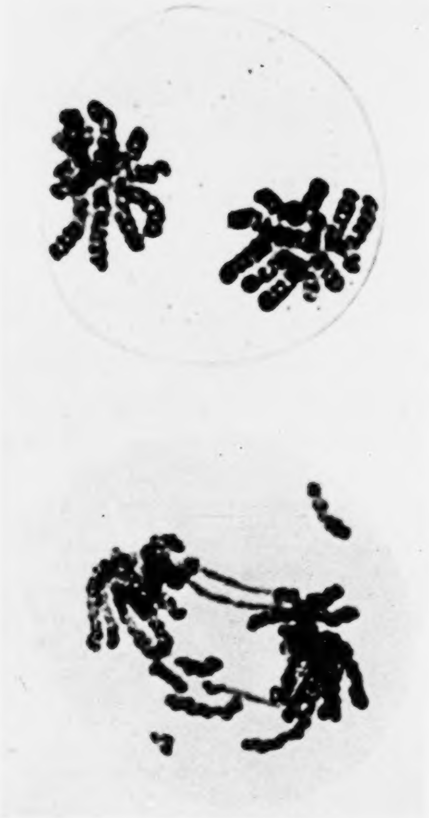


An autoradiograph of a fern frond made after the plant had taken in a solution containing radioactive sulfur 35.

Perhaps the most rewarding uses of radioisotopes have been in medical research, diagnosis and therapy. For example, tracers can help to determine the rate of flow of blood through the heart and to the limbs, thus aiding in the diagnosis of abnormal conditions. Intense doses of radiation can do serious damage to living cells. Diseased cells are often more easily damaged than normal cells. Radiation can, therefore, be used to treat some diseases, such as cancer. Some parts of the body take up particular elements preferentially. For example, the thyroid gland absorbs iodine easily. Specially prepared radioisotopes of such elements can be administered to the victims of certain diseases, thus supplying desired radioactivities right at the site of the disease. This method has been used in the treatment of cancer of the thyroid gland, blood diseases and brain tumors and in the diagnosis of thyroid, liver and kidney ailments.

Table 24.1 summarizes the use of a few radioisotopes, most of which are produced by neutron bombardment in nuclear reactors. Such uses suggest the promise that nuclear physics holds for the future. Indeed, they symbolize the meaning of science at its best: research in science lays open to our understanding the secrets of nature—and from the application of this knowledge to human needs, all mankind can benefit.





At the top, the damaged trees surround a radioactive cesium 137 capsule which had been kept there for nearly 6 months in an experiment to study the effects of ionizing radiation on biological systems.

The upper portion of the photo at the left shows normal plant cell chromosomes divided into 2 groups. Below that the same cell is shown after x-ray exposure. Fragments and bridges between groups are typical radiation-induced abnormalities.

Above is a 14,000 yr. old burial site being uncovered by an archeological team near the Aswan Reservoir. The age of the burial site is determined by carbon-14 dating (described in SG 22.9) of scraps of wood or charcoal found in it.

24.1 Suppose that $_6C^{13}$ is formed by adding a neutron of a $_6C^{12}$ atom. Calculate the binding energy due to that neutron in C^{13}; the atomic masses of C^{12} and C^{13} are 12.000000 and 13.003354 amu. 4.95 MeV

24.2 The atomic mass of He^4 is 4.00260 amu; what is the average binding energy per particle? 7.07 MeV/nucleon

24.3 Suppose that a proton with negligible kinetic energy induces the following reaction:

$$_3Li^7 + {}_1H^1 \longrightarrow {}_2He^4 + {}_2He^4.$$

If the lithium nucleus were initially at rest, what would be the relative directions of the two α particles? What would be the kinetic energy of each α particle? opposite directions, each with KE of 8.65 MeV

24.4 The first nuclear transmutation (produced by Rutherford in 1919) was the reaction:

$$_7N^{14} + {}_2He^4 \longrightarrow {}_8O^{17} + {}_1H^1.$$

The atomic masses involved are:

N^{14}: 14.003074 amu
O^{17}: 16.999134 amu
$_2He^4$: 4.002604 amu
$_1H^1$: 1.007825 amu

Is energy absorbed or released in this reaction? How much energy (in MeV) is involved? absorbed, 1.19 MeV.

24.5 In an experiment on the reaction of SG 24.4, the α particles used had a kinetic energy of 7.68 MeV, and the energy of the protons was 5.93 MeV. What was the "recoil" energy of the O^{17} nucleus? 0.56 MeV.

24.6 Calculate the amount of energy (in MeV) liberated in the following nuclear reaction:

$$_7N^{14} + {}_1H^2 \longrightarrow {}_7N^{15} + {}_1H^1. \qquad 8.61 \text{ MeV}$$

The atomic masses are:

N^{14}: 14.003074
H^2 : 2.014102
N^{15}: 15.000108
H^1 : 1.007825

24.7 Appreciable amounts of the uranium isotope $_{92}U^{233}$ do not occur outside the laboratory; $_{92}U^{233}$ is formed after the thorium nucleus $_{90}Th^{232}$ has captured a neutron. Give the probable steps leading from $_{90}Th^{232}$ to $_{92}U^{233}$. Neutron capture, β decay. β decay.

24.8 Use Fig. 24.1a to find the binding energies for U^{235}, Ba^{141} and Kr^{92}. Use these values to show that the energy released in the fission of U^{235} is approximately 200 MeV. U^{235}: 1790 MeV Ba^{141}: 1180 MeV. Kr^{92}: 800 MeV

24.9 Possible end-products of U^{235} fission, when provoked by capture of slow neutrons, are $_{57}La^{139}$ and $_{42}Mo^{95}$. This reaction may be described by the equation:

$$_{92}U^{235} + {}_0n^1 \longrightarrow {}_{57}La^{139} + {}_{42}Mo^{95} + 2\,{}_0n^1 + 7({}_{-1}e^0).$$

The mass of $_{57}La^{139}$ is 138.8061 amu; that of $_{42}Mo^{95}$ is 94.9057 amu. How much energy is released per atom in this particular fission? The mass of the seven electrons may be neglected. 208 MeV.

24.10 Loss of neutrons from a mass of fissionable material depends on its shape as well as its size. For some shapes, it is impossible to reach a critical size because the neutron loss through the surface is too great. With what shape would a mass of fissionable material suffer the least loss of neutrons from the surface? The most? least loss — spherical; most loss - flat sheet.

24.11 Why are the high temperatures produced by the explosion of a fission bomb necessary to initiate fusion in a thermonuclear device? very high KE protons required.

24.12 It is generally agreed that stars are formed when vast clouds of hydrogen gas collapse under the mutual gravitational attraction of their particles. How do fusion reactions begin in such stars? high enough temperatures result from the collapse.

24.13 One of the energy sources in the sun is the production of helium nuclei by four protons as described in Sec. 24.9: $4\,{}_1H^1 \longrightarrow {}_2He^4 + 2\,{}_{+1}e^0$. Show that about 26 MeV of energy are released in each cycle.

24.14 Fusion reactions in the sun convert a vast amount of hydrogen into radiant energy each second.

(a) Knowing that the energy output of the sun is 3.90×10^{26} joules/sec, calculate the rate at which the sun is losing mass. 4.33×10^9 Kg/Sec

(b) Convert the value 3.90×10^{26} joules/sec to horsepower. (Recall that 1 horsepower is equivalent to 746 watts). 5.23×10^{23} horsepower

24.15 A source of energy in the sun may be the "carbon cycle," proposed by Hans Bethe, which is outlined below. Complete the six steps of the cycle.

$${}_6C^{12} + {}_1H^1 \longrightarrow \underline{{}_7N^{13}} + \gamma$$

$$\underline{{}_7N^{13}} \longrightarrow {}_6C^{13} + {}_{+1}e^0 + \nu$$

$${}_6C^{13} + {}_1H^1 \longrightarrow \underline{{}_7N^{14}} + \gamma$$

$$\underline{{}_7N^{14}} + {}_1H^1 \longrightarrow {}_8O^{15} + \gamma$$

$${}_8O^{15} \longrightarrow \underline{{}_7N^{15}} + {}_{+1}e^0 + \nu$$

$$\underline{{}_7N^{15}} + {}_1H^1 \longrightarrow {}_6C^{12} + {}_2He^4$$

24.16 Another reaction which may take place in the sun is:

$$He^3 + He^4 \longrightarrow Be^7 + \gamma.$$

The atomic mass of He^3 is 3.016030 amu, and that of Be^7 is 7.016929. Is energy absorbed or released? How much energy? released; 1.59 MeV.

24.17 The atomic masses of ${}_{92}U^{233}$ and ${}_{92}U^{234}$ are 233.039498 and 234.040900 amu. The activation energy for the fission of the nucleus ${}_{92}U^{234}$ is 4.6 MeV. Is U^{233} fissionable by slow neutrons?

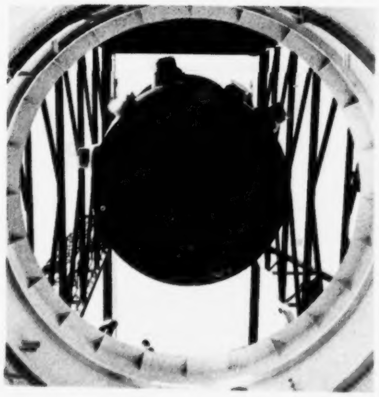
Yes, because the excitation energy is greater than the activation energy.

24.18 Bombardment of ${}_{94}Pu^{241}$ with slow neutrons sometimes leads to the reaction:

$${}_{94}Pu^{241} + {}_0n^1 \longrightarrow {}_{94}Pu^{242} + \gamma.$$

The atomic masses of Pu^{241} and Pu^{242} are 241.056711 amu and 242.058710 amu. The activation energy of Pu^{241} is 5.0 MeV. Is Pu^{241} fissionable with slow neutrons?

Yes.



Epilogue In this unit we have traced the development of nuclear physics from the discovery of radioactivity to current work in nuclear fission and fusion. We have seen how radioactivity provided a place to start from and tools to work with. In radioactivity man found the naturally occurring transmutation of elements that made it possible for him to achieve the transmutations sought by the alchemists. The naturally occurring radioactive series pointed to the existence of isotopes, both radioactive and stable. Artificial transmutation has increased by many hundreds the number of atomic species available for study and use.

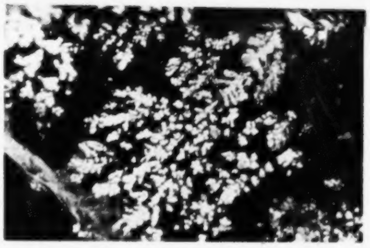
Nuclear physicists and chemists study the reactions of the stable and radioactive nuclides; and so nuclide charts and tables grow. The collection and correlation of a vast body of experimental data remind us of the work of the nineteenth-century chemists and spectroscopists. Nuclear models are built, changed and replaced by newer and, perhaps, better models. But the detailed nature of nuclear forces is still the subject of much research, especially in the field of high-energy physics.

But that is only one of the fields that remains to be explored. The nucleus also has magnetic properties which affect the behavior of atoms. Sometimes it helps to study these properties when the atoms of matter are at very low temperatures, as close to absolute zero as we can get them. Nuclear physics overlaps with solid-state physics and with low-temperature physics; strange and wonderful things happen—and quanta again help us understand them.

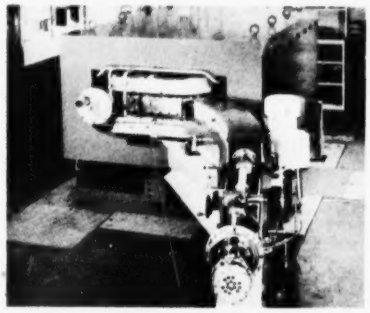
The study of light through the development of devices such as the laser attracts many physicists. These devices are made possible by, and contribute to, our increasing understanding of how electrons in complex atomic systems jump from one energy state to another—and how they can be made to jump where and when we want them to.

The properties of liquids are still only imperfectly understood after much study. Thales of Miletus was perhaps the first man on record to make a large-scale scientific speculation when he proposed, over twenty-six centuries ago, that maybe everything in the world is basically made of water in combinations of its various states. Thales was wrong, but even today we are trying to develop an adequate theory of the behavior of water molecules.

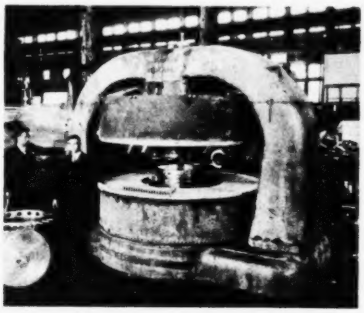
All the subjects we have mentioned touch on engineering, where physics and other disciplines are made to work for us. All of the engineering fields involve physics. Nuclear engineering and space engineering are the most recent and, at the moment, perhaps the most glamorous. But today the chemical engineer, the mechanical engineer and the metallurgist all use quantum mechanics. They must understand the properties of atoms and atomic nuclei, because it is no longer enough to know only the properties of matter in bulk.

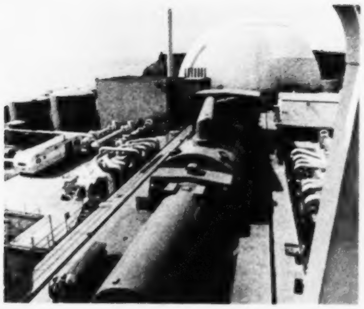


The radiations we have talked about—α, β and γ rays—are tools for industry, biology and medicine. They help to cure, preserve, study, understand. Neutrons are not only constituents of the nucleus, they are also probes for studies in science and in industry.



So our study of atoms and nuclei, indeed our whole course, has been an introduction not only to physics but also to the many fields with which physics is closely linked. It has been an introduction to an ever-expanding world in which much is known and understood, but where much more—and perhaps the most wonderful part—is waiting to be discovered.





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Brief Answers to Study Guide

Chapter 21

21.1 (a) The radioactivity of thorium was proportional to the amount of thorium.
(b) new radioactive elements polonium and radium

21.2 (a) 1.2×10^{-13} joule
(b) 0.75 MeV

21.3 (a) 5.7×10^{-2} m
(b) 420 m
(c) 7350:1

21.4 (a) 1.0×10^{4} N/coul
(b) 1.0×10^{3} volts
(c) undeflected

21.5 (a) γ (f) α
(b) α (g) β
(c) α (h) α
(d) γ (i) α
(e) γ (j) β

21.6 (a) Radium decayed into radon (a gas) which decays into radium A which is deposited on nearby objects.
(b) The residue contained daughters of high activity (short half-life).
(c) The uranium compound continually decayed into more active daughters, but daughters in the residue were not replaced as they decayed.

21.7 (a) 1/2
(b) 3/4
(c) Assume the products of decay were not themselves radioactive.

21.8 (a) graph
(b) 8.31×10^{19} atoms
(c) 5.0×10^{20} atoms

21.9 (a) 5.7×10^{-13} joules/disintegration
(b) 45 watts

21.10 3.70×10^{5} disintegrations/sec

21.11 5.0×10^{-3}/min
5×10^{3} atoms/min
Yes

21.12 10% of the 90% or 9% of the original.

Chapter 22

22.1 Isotopes of an element have same Z.

22.2 Determine if its chemical properties are unique.

22.3 (a) The lighter particles would diffuse away from the liquid surface more rapidly after evaporation, hence fewer of them would re-enter the liquid.
(b) The hydrogen isotopes have the largest ratio of isotopic masses (2:1) and hence the largest ratio of speeds ($1:\sqrt{2}$).

22.4 (a) 0.054 m
(b) 5.64 m
(c) 0.005 m

22.5 (a) ${}_{82}Pb^{212}$ ${}_{83}Bi^{212} + {}_{-1}e^{0}$
(b) ${}_{83}Bi^{212}$ ${}_{84}Po^{212} + {}_{-1}e^{0}$
(c) ${}_{84}Po^{212}$ ${}_{82}Pb^{201} + {}_{2}He^{4}$

22.6 chart, the end product being ${}_{82}Pb^{207}$.

22.7 diagram, ending with ${}_{82}Pb^{208}$. The alternatives are in the mode of decay of ${}_{84}Po^{216}$ and ${}_{83}Bi^{216}$.

22.8 decay diagram, the modes of decay are β, α, α, β, α, α.

22.9 4000 years
25000 years

22.10 (a) 12.011 amu
(b) 6.941 amu
(c) 207.2 amu

22.11 4.0015 amu

Chapter 23

23.1 235 is not divisible by 4.

23.2 235 protons
143 electrons

23.3 (a) ${}_{6}C^{13}$ (b) ${}_{12}Mg^{26}$ (c) ${}_{14}Si^{30}$
(d) ${}_{16}S^{32}$ (e) ${}_{19}K^{37}$

23.4 (a) ${}_{2}He^{3}$ (b) ${}_{3}Li^{6}$
(c) ${}_{4}Be^{8}$ (d) ${}_{0}n^{1}$

23.5 (a) γ (b) Al^{28}
(c) Mg^{24} (d) Mg^{25}
The same nuclide bombarded by different particles will yield different products.

23.6 Nitrogen nuclei are an order of magnitude more massive than hydrogen.

23.7 1.24 amu
6.9%

23.8 table

23.9 (a) 78 (b) 79 (c) 80

23.10 The missing product nuclide in each case is the same. ${}_{11}Na^{24}$.

23.11 description

23.12 explanation

23.13 explanation

Chapter 24

24.1 4.95 MeV

24.2 7.07 MeV/nucleon

24.3 opposite directions,
each with KE of 8.65 MeV

24.4 absorbed,
1.19 MeV

24.5 0.56 MeV

24.6 8.61 MeV

24.7 neutron capture,
β-decay
β-decay

24.8 U^{235}: 1790 MeV
Ba^{141}: 1180 MeV
Kr^{92}: 800 MeV

24.9 208 MeV

24.10 least loss—spherical
most loss—flat sheet

24.11 very high KE protons required

24.12 high enough temperatures result from the collapse

24.13 "proof"

24.14 (a) 4.33×10^{9} kg/sec
(b) 5.23×10^{23} horsepower

24.15 (1) ${}_{7}N^{13}$ (4) ${}_{7}N^{14}$
(2) ${}_{7}N^{13}$ (5) ${}_{7}N^{15}$
(3) ${}_{7}N^{14}$ (6) ${}_{7}N^{15}$

24.16 released
1.59 MeV

24.17 Yes, because the excitation energy is greater than the activation energy.

24.18 Yes

Appendix A Some Physical Constants and Conversion Factors

Name	Value
Speed of light	3.00×10^{8} m/sec
Planck's constant	6.63×10^{-34} J·sec
Charge of electron	-1.60×10^{-19} coul
Rest mass of electron	9.11×10^{-31} kg = 0.000549 amu
Rest mass of proton	1.67×10^{-27} kg = 1.007276 amu
Rest mass of neutron	1.67×10^{-27} kg = 1.008665 amu
Mass of neutral hydrogen atom	1.67×10^{-27} kg = 1.007825 amu

1 eV = 1.60×10^{-13} J

1 MeV = 10^{6} eV

1 amu = 931 MeV

Appendix B Some "Elementary" Particles

Family name	Particle name	Symbol	Rest mass*	Electric charge	Antiparticle	Average lifetime (seconds)
Photon	photon	γ (gamma ray)	0	neutral	same particle	infinite
Leptons	neutrino	ν, ν_μ	0	neutral	$\bar{\nu}$, $\bar{\nu}_\mu$	infinite
	electron	e^-	1	netative	e^+ (positron)	infinite
	μ-meson (muon)	μ^-	207	negative	μ^+	10^{-6}
Mesons	π-mesons (pions)	π^+	273	positive	π^- same as	10^{-8}
		π^-	273	negative	π^+ the	10^{-8}
		π^0	264	neutral	π^0 particles	10^{-16}
	K-mesons (Kaons)	K^+	966	positive	K^- (negative)	10^{-10} and 10^{-7}
		K^0	974	neutral	$\bar{K}^0$	
	η-meson (eta)	η^0	1073	neutral	$\bar{\eta}^0$	10^{-18}
Baryons	proton	p	1836	positive	$\bar{p}$ (antiproton)	infinite
	neutron	n	1839	neutral	$\bar{n}$ (antineutron)	10^{3}
	lambda	Λ^0	2182	neutral	$\bar{\Lambda}^0$	10^{-10}
	sigma	Σ^+	2328	positive	$\bar{\Sigma}^-$ (negative)	10^{-10}
		Σ^-	2341	negative	$\bar{\Sigma}^+$ (positive)	10^{-10}
		Σ^0	2332	neutral	$\bar{\Sigma}^0$	10^{-20}
	xi	Ξ^-	2580	negative	$\bar{\Xi}^+$ (positive)	10^{-10}
		Ξ^+	2570	neutral	$\bar{\Xi}^0$	10^{-10}
	omega	Ω^-	3290	negative	$\bar{\Omega}^+$	10^{-10}

* Mass of electron is 1 unit on this scale

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Answers to End of Section Questions

Chapter 21

Q1 It was phosphorescent.

Q2 No treatment was needed—the emission was spontaneous.

Q3 Their apparent constancy—they couldn't be turned off or even varied.

Q4 It isn't—although slight differences might be observed because of the other element absorbing some of the radiation.

Q5 The radioactivity was much greater than expected for the amount of uranium in the ore.

Q6 separating it from barium, which is almost identical chemically

Q7 from most to least penetrating: γ, β, α

Q8 β particles were found to have the same q/m ratio as electrons.

Q9 α rays were deflected much less than β rays by a magnetic field.

Q10 Its emission spectrum, when caused to glow by an electric discharge, was the same as helium's.

Q11 It occurs when only a single pure element is present, and isn't affected by chemical combinations of that element.

Q12 The mass of a daughter was found to be less than the mass of the parent by the mass of a helium nucleus.

Q13 1) Many of the substances in a series have the same chemical properties.
2) There are only small percentage differences in atomic mass.
3) Many of the substances decayed very rapidly into something else; all three kinds of rays are given off by the mixture.

Q14 1/16 of it

Q15 No definite prediction is possible. As usual, the odds are 50:50 that one of them will disintegrate. (But the odds are 1 in 4 that both will, and 1 in 4 that neither will.)

Chapter 22

Q1 They were chemically the same as previously known elements.

Q2 decreases 4 units; stays essentially the same

Q3 decreases by 2 + charges; increases by 1 + charge

Q4 by subtracting α particle masses from the mass of the parent of the decay series

Q5 The ions coming out of the "velocity selector" all have the same speed.

Q6 1) faint second line in mass spectrum of pure neon
2) different atomic masses of samples of neon separated by diffusion
3) more intense second line in mass spectrum of one of the samples separated by diffusion

Q7 More massive atoms have a lower average speed and so diffuse more slowly than less massive ones.

Q8 $_{78}Pt^{194}$; platinum.

Q9 (A-4)

Q10 (Z+1)

Q11 an isotope of hydrogen with twice the atomic mass of ordinary hydrogen

Q12 The third isotope has a very low abundance.

Q13 $_{6}C^{12}$

Chapter 23

Q1 Several atomic masses (which were not recognized as the average of several isotopes) were not close to whole multiples of the atomic mass of hydrogen.

Q2 12 protons and 6 electrons

Q3 In a cloud chamber there was no after-collision track for the α particle.

Q4 The way it knocked protons out of paraffin would be for γ rays a violation of the principles of energy and momentum conservation.

Q5 A neutron has no charge, and so isn't deflected by magnetic or electric fields, nor does it leaves a track in cloud chamber.

Q6 7 protons and 7 neutrons

Q7 a nucleus of 2 protons and 2 neutrons, surrounded by 2 electrons

Q8 A neutron in the nucleus changes into a proton and a β particle, which immediately escapes.

Q9 Without the extra particle, there was no way to explain the disappearance of energy in β-decay.

Q10 The repulsive electric force exerted by the large charge of the heavy nucleus on an α particle prevents it from reaching the nucleus.

Q11 Protons have only a single charge.

Q12 They have no electric charge and so are not repelled by nuclei.

Q13 False: Neutron capture, for example, can produce a heavier isotope of the same element.

Q14 $_{14}Si^{28}$

Q15 $_{6}C^{13}$. 7 protons, 6 neutrons before; 6 protons, 7 neutrons after.

Chapter 24

Q1 No, in some nuclear reactions energy is absorbed.

Q2 It can go off as γ rays or as the KE of the product particles.

Q3 A nuclide with a high *average* binding energy is more stable.

Q4 No. Light nuclei are lower on the curve than heavy nuclei.

Q5 capture of a neutron by a uranium nucleus, then the β decay of the new nucleus

Q6 neutrons

Q7 a substance which slows down neutrons

Q8 It slows down neutrons well (because of the abundance of H atoms), but it also absorbs many (to form "heavy" water).

Q9 The positively charged nuclei repel each other and high speeds are necessary for the nuclei to come near enough in collisions to fuse.

Q10 Since at very high temperatures the gas is ionized, a properly shaped magnetic field could deflect the charged particles away from the walls.

Q11 decreasing

Q12 The protons in a nucleus repel each other with intense electric forces.

Q13 The average binding energy curve suggests that each particle in the nucleus is bound only by its immediate neighbors.

Q14 An excited nucleus becomes distorted in shape; electric repulsion between bulges then forces them apart.

Q15 The excitation energy resulting from neutron capture alone is less than the activation energy required for fission.

Q16 They correspond to completed shells (or sets of energy states) of protons and neutrons in the nucleus.

Q17 Your answer should be that this is not a sensible question. Both models are incomplete; the point is not to decide between them, but to blend them into a more complete general model.

Acknowledgments

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P. 35 Soddy, Frederick.

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P. 57 Rutherford, Ernest, "Collision of Alpha Particles with Light Atoms. IV. An Anomalous Effect in Nitrogen," *Philosophical Magazine*, Series VI, Vol. 37, p. 587.

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Suggested Answers to Test

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Test B 105
Test C 108
Test D 109

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Overview of Unit 6

The main purpose of Unit 6 is to trace the development of our ideas of the constitution and structure of the atomic nucleus. The story line is simpler than that of Unit 5 and extends over a much shorter time interval—from 1896 to the present. The material has been chosen to trace the story and at the same time, to accomplish some additional purposes. These are: first, to emphasize important concepts from earlier units, for example, the use and importance of the principles of conservation of energy and momentum, the motion of charged particles in electric and magnetic fields; second, to relate the physics to practical applications, and to social and economic problems. The material of Unit 6 is more amenable to these purposes (in the space available) than was the material of Unit 5.

The story of the atomic nucleus starts with the discovery of radioactivity. The phenomena of radioactivity furnished information about atomic transformations that were shown later to occur in the nucleus. Radioactivity supplied the first projectiles (the α particles) that made possible the discovery of the atomic nucleus and of artificial transmutation and nuclear reactions. The investigation of radioactivity also led to the concept of isotopes. Hence, the study of radioactivity opened several roads that led to the nucleus and its properties. Chapter 21 deals, therefore, with the discovery of radioactivity, the phenomena of radioactivity, and the theory of radioactive transformations. We are led in a direct way to the discovery of isotopes, treated in Chapter 22. The quantitative investigation of isotopes by means of the mass spectrometer made possible the measurement of the masses of individual atoms. These measurements are based on the motion of charged particles in electric and magnetic fields. A large amount of data was obtained on isotopic masses and natural abundance, which made possible theories concerning the composition of the nucleus. These theories are treated in Chapter 23 which includes much of the heart of Unit 6. That chapter provides a fine example of the interplay between theory and experiment. The first hypothesis of the constitution of the nucleus, the proton-electron hypothesis, was unsuccessful. Further experimentation led to the discovery of artificial transmutation which led, in turn, to the discovery of the neutron. The proton-neutron hypothesis of the constitution was then possible. The discovery of artificial transmutation and nuclear reactions opened up the field of radiochemistry, and led to the invention of charged-particle accelerators. The use of these machines resulted in the accumulation of an enormous amount of information, in analogy to the development of chemistry in the 19th century. The phenomena studied in this chapter are closely dependent on the principles of conservation of energy and momentum (the neutron and neutrino).

The information developed in Chapters 22 and 23 makes possible the quantitative study of the energy balance in nuclear reactions and led to the concept of nuclear binding energy. These are the first subjects studied in Chapter 24. They are intimately connected with nuclear fission and nuclear fusion and the vast release of energy in these reactions. Hence, nuclear fission is studied in some detail, along with its practical applications and industrial, economic, and political consequences. The energy release in these nuclear reactions focuses attention on the forces holding the nucleus together, and on models of nuclear structure. Nuclear physics is far from complete, and Unit 6 ends with hints of problems and possibilities that remain.

Experiments

E44*	Random events
E45*	Range of alpha and beta particles
E46*	Half-Life I
E47	Half-Life II
E48	Radioactive Tracers

Demonstrations

D59	Mineral audioradiograph
D60	Naturally occurring radioactivity
D61	Mass spectrograph
D62	Aston Analogue

Transparencies

T40	Separation of α , β, γ rays
T41	Rutherford's α Particle "mousetrap"
T42	Radioactive disintegration series
T43	Radioactive decay curve
T44	Radioactive displacement rules
T45	Mass spectrograph
T46	Chart of the nuclides
T47	Nuclear equations
T48	Binding energy curves

Loops

L49	Collisions with an unknown object

Non-Project Physics Loops

L6-1	Radioactive decay
L6-2	Thomson's positive ray parabolas
L6-3	Aston's mass spectrograph
L6-4	Nuclear reactions
L6-5	Critical size

Unit Overview

Films (16mm)

F47	Discovery of radioactivity
F48	U238 radioactivity series
F49	Random events
F50	Long time intervals
F51	Isotopes
F52	The linear accelerator
F53	Positron-electron annihilation
F54	Fission

Reader Articles

R1	Rutherford
R2	The Nature of the Alpha Particle
R3	Some Personal Notes on the Search for the Neutron
R4	Antiprotons
R5	The Tracks of Nuclear Particles
R6	The Spark Chamber
R7	The Evolution of the Cyclotron
R8	The Cyclotron As Seen By...
R9	CERN
R10	Mr. Tompkins Tastes a Japanese Meal
R11	Models of the Nucleus
R12	Power from the Stars
R13	Success
R14	The Nuclear Energy Revolution
R15	Conservation Laws
R16	The Fall of Parity
R17	Can Time Go Backward?
R18	A Report to the Secretary of War
R19	Twentieth Birthday of the Atomic Age
R20	Calling All Stars
R21	Tasks for a World Without War
R22	One Scientist and his View of Science
R23	The Development of the Space-Time View of Quantum Electrodynamics
R24	Physics and Mathematics

UNIT SIX MULTI-MEDIA SCHEDULE (Details on following pages)

1 Introduction to Unit 6 Unit 6 Prologue	2 LAB STATIONS: Detection of Radioactivity	3 LIBRARY DAY Students look for research topics	4 LAB STATIONS: Behavior of nuclear particles
1a Text: 21.1 – 21.3	2a Text: 21.4 – 21.5	3a Text: 22.1 – 22.2 Reader: Nature of Alpha Particles, Rutherford.	4a Text: 22.3-22.4
5 LIBRARY DAY Continue research	6 EXPERIMENTS on Radioactivity	7 Experiments con't.	8 Experiments con't.
5a Text: 23.1 – 23.3	6a Write up experiments	7a Write up experiments	8a Write up experiments
9 FOLLOW-UP DISCUSSION of Experiments	10 PROBLEM-SOLVING DAY	11 READING AND PLANNING	12 LAB STATIONS: Models and Applications
9a Problems from Chapters 21 and 22	10a Finish problems	11a Reader: Success, Fermi.	12a Text: 23.4-23.6
13 DISCUSS CONTRACTS Students draw up contracts	14 Students work on contracts and research; teacher assists.	15 Continue work on contracts	16 TEACHER PRESENTATION
13a Text: 23.6 – 23.7	14a Text: 24.1 – 24.4	15a Text: 24.5 – 24.8	16a
17 FISSION REACTORS	18 TEACHER PRESENTATION on Fusion (quantitative)	19 Continue fusion	20 STUDENT REPORTS from research
17a	18a	19a	20a
21 Student reports continued	22 Student reports continued	23 REVIEW OF UNIT 6 Optional: College Bowl-Type Quiz	24 UNIT 6 TEST 25 FILM: The Strange Case of the Cosmic Rays
21a	22a Reader: Calling all Stars, Szilard	23a Unit 6 Epilogue	24a Review

Details of the Multi-Media Schedule

Day 1

Teacher introduction to Unit 6

Points to make:

1. that there is a stage beyond atoms
2. new techniques and ideas are required in order to study what one cannot see

Film: Discovery of Radioactivity (color), International Film Bureau

Small group discussion of film (Provide guide questions)

Day 2

Lab stations: Detection of Radioactivity

1. Cloud chamber, Project Physics type. Provide sources so that students can compare tracks of alpha and beta particles.
2. Geiger counter; Project Physics or other type is sufficient. Provide alpha and beta sources.
3. Electroscope. Observe discharge rate of electroscope with and without presence of radioactive sources.
4. 3-D viewer and pictures from bubble chamber.
5. Spinthariscope. Many designs are available for purchase or construction, all require time for eyes to become dark adapted.
6. Photographic plate. See Teacher Guide for details.

Day 3

Library Day: Students are given an opportunity to pick area for an individual study.

Some possible topics:

- Accelerators (or specific accelerator, e.g., Brookhaven)
- Detection devices (or specific device, e.g., bubble chamber)
- Types of research with isotopes (specifically: medicine, biology)
- Political issues of nuclear science: detection of tests, control of power, financing of research, etc.
- Engineering applications of nuclear power
- The future of the nuclear age: nuclear power, cheap power, etc.
- New Particles: Quarks, Ω^-
- The "8-fold way"
- Radiation safety

Day 4

Lab Stations: Behavior of Nuclear Particles

Use same stations as for Day 2, but emphasize the behavorial characteristics of particles.

Investigate absorption, magnetic deflection, scattering, and inverse-square law of radiation intensity. (Be careful about the inverse-square law because air is a good absorber of radiation.)

Day 5

Library Day

Help students find topics relating to Unit 6 concepts and consistent with their ability and interests. In general, student should (a) find a topic of interest, (b) read up on it, (c) tell the rest of the class about it on Days 20-22.

Days 6,7, 8 Experiments on radioactivity

Students do one experiment each day.

E 44 Random events
E 45 Range of alpha and beta particles
E 46 Half-life 1

Day 9

Summary

Teacher leads class in summarizing experiments and results.

Day 10

Problem-solving day

Select appropriate end-of-chapter problems on displacement rules, half-life, decay constant, etc.

Day 11

Student activity

Students continue to read and plan for contract*. Give students latitude in the way topics can be described to class. For example, a student who studies reactors may wish to make a model to show; a student who studies political implications of nuclear power may wish to write an essay to read; and students studying the financing of nuclear research may want to dramatize a make-believe request in front of the class.

Day 12

Lab Stations: Models and Applications

1. Model of mass spectrograph. Drop steel balls of various masses past a strong magnet and note where they land. Compare principle to mass spectrograph.
2. Model of nuclear scattering. Mount magnet under glass tray. Use magnetic discs and beads to show Rutherford scattering. Other models possible.
3. Model of chain reaction. "Mousetrap-and-cork" model is ideal; a set of dominoes arranged in a pyramid also illustrates the reaction.
4. Film loop 49. Collision with unknown object.
5. Dice model of decay. Twenty-sided and eight-sided dice used to show decay rates. See Teacher Guide.
6. Model cyclotron. Place a marble in the center of a flat board (approx. 24" × 24"). Tilt the board back and forth to cause the marble to roll faster and faster in a circular path. Compare principle to cyclotron.

Days 13, 14, 15

Ditto a contract form for students to fill in. Contract should contain a bibliography of material studied and a description of the way it will be presented to class. You may want to have student specify what grade he will receive for successful completion of contract terms. This technique seems to appeal especially to slower students. Help students write reasonable contracts.

Day 16

Lecture presentation on fission

Show quantity of ΔE from Δm. Avoid homework assignments here to allow students to concentrate on projects.

Day 17

Fission (continued)

Local power companies often have information on nuclear power reactors that provides an extension of this topic. A good wrap-up film (10 min.) is Principles of Nuclear Fission (McGraw-Hill).

Day 18

Lecture presentation on fusion.

Show quantitative relationships of ΔE and Δm.

Day 19

Continue Day 18.

Days 20, 21, 22

Student report day

Student presentations, demonstrations, and dramatizations are given to class.

Day 23

Review for Unit 6 test

College Bowl-type quiz could be set up by a student or students as their contract project. All the class can participate as judges, scorers, timers and team members.

Day 24

Unit 6 test.

Day 25

Film:

The Strange Case of the Cosmic Rays
Available through local telephone office (58 min., color).

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*A contract is an agreement, between teacher and student, which relates the nature and amount of work to be performed by the student to his expected grade. It can be either verbal or written and can exist in various degrees of intensity depending upon the circumstances.

Chapter 21 Schedule Blocks

Chapter 21: Radioactivity

Read 21.1–21.3, E44*

Lab –
Random events

Read 21.4–21.5

Post lab
and/or problem
seminar

Read E45*

Lab –
Range of alpha
and beta
particles

Read 21.6–21.7

Post lab
and/or
problem
seminar

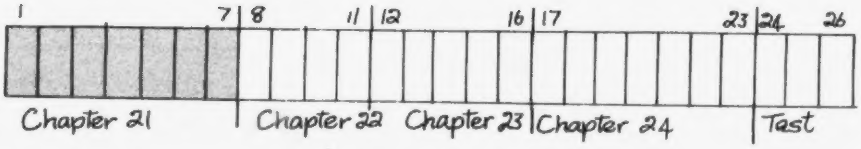
Read 21.8, E46*

Lab –
Half-Life I

Review

Post lab
and/or
problem
seminar

Test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Test

Chapter 21 Resources Chart

Text	Schedule	Problems			Experiments and Teacher Demonstration
21.1 Bequerel's discovery					E44* Random events D59 Mineral Audioradiograph
21.2 Other radioactive elements are discovered.			1		D60 Naturally occurring radioactivity
21.3 The penetrating power of the radiation: α, β and γ rays.		2			E45* Range of Alpha and Beta particles
21.4 The charge and mass of α, β and γ rays.			3	4	
21.5 The identity of rays: Rutherford's "mousetrap."					
21.6 Radioactive transformation		5			
21.7 Radioactive decay series.				6	
21.8 Decay rate and half life.		10	7 9 11 12	8	E46* Half-life I E47 Half-life II

Chapter 21 Resources Chart

Transparencies, Loops, Films, Reader, Programmed Instruction	Student Activities
F47 Discovery of radioactivity	
L6-1 Radioactive Decay	Ionization by radioactivity
R1 Rutherford	Measuring the energy of Beta radiation
T40 Separation of α, β, γ rays	Magnetic deflection of Beta rays
T41 Rutherford's α particle "Mousetrap" R2 The nature of the alpha particle	
F48 U238 Radioactivity series	
T42 Radioactive disintegration series	
F49 Random events T43 Radioactive decay curve	A sweet demonstration Exponential decay in concentration.

Chapter 21 Experiment Summaries

Summary of Experiment 44*: Random Events

The student observes a series of random events in each of three different situations and seeks a pattern of behavior common to all of them. The apparatus and techniques are used again in the following experiment with alpha and beta particles.

Apparatus for each student group

A. tray containing 120 twenty-sided dice
graph paper

B. continuous cloud chamber and alpha-particle source
cardboard barrier to confine alpha

dry ice or source of CO_2 snow
methanol (methyl alcohol)
light source
graph paper

C. beta-particle source
Geiger counter with its power supply, pulse divider, amplifier and loudspeaker
graph paper
radioisotopes (order well ahead)
planchets
10-ml pipettes with rubber bulb OR
disposable plastic syringes
disposable plastic gloves

Summary of Experiment 45*: Range of Alpha and Beta Particles

The range of alpha particles is measured in a cloud chamber and the range of beta particles is measured with a Geiger counter, using apparatus and techniques from the previous experiment in both cases.

Equipment

For each student group:

A. alpha-particle source
continuous cloud chamber
cardboard barrier used in random events experiment
dry ice or CO_2 source of dry-ice snow
methanol (methyl alcohol)
clock with second hand
light source
centimeter ruler

B. beta-particle source
six 2" x 2" squares of shirt cardboard and/or thin aluminum foil
Geiger tube with its power supply, pulse divider, amplifier and loudspeaker
graph paper
clock with second hand
filter paper, 25 mm disc
Geiger counter with power supply, pulse divider and amplifier
stopper, #3 neoprene, to fit funnel
2 graduated cylinders, 25 ml
stopwatch or clock with second hand
ringstand and clamp for funnel
filter pump
ammonium phosphomolybdate
thorium nitrate solution
filter flask, 250 ml, with tubing to connect to pump
diluted nitric acid
distilled or deionized water in beaker or wash bottle
bottle or flask for catching filtrate

Summary of Experiment 46*: Half-Life

Three examples of exponential decay are measured in this exercise and in each case a decay curve is plotted and half-life and decay constant computed. The three examples are independent of each other, making it possible to omit one or two of them without loss to the essnetial idea of the experiment. No knowledge of logarithms or exponents is required although it may be made use of if desired.

Equipment

A. tray containing 120 twenty-sided dice graph paper

B. resistance of about 10^4 ohms (see Teacher Guide for discussion
capacitor of about 6000 μF
(dry cell, 1-1/2 volts or 6 volts)
voltmeter (0 - 2.5 volts dc)
switch (optional)
Connecting wires
graph paper

C. polyethylene Buchner funnel
(26 mm plate diameter)

Summary of Experiment 47: Half-Life II

This is a very simple and clean half-life experiment. Lead 212 is deposited on negatively charged aluminum foil inside a vessel containing thorium nitrate. Although the decay scheme proceeds through several more radioactive nuclides before the stable lead 208 is reached, all the others have much shorter half-lives than lead 212. The decay of lead 212 is therefore the rate-determining process and students should find that the sample does have a constant half-life of about 10.5 hours ($T_{\frac{1}{2}}$ for lead 212 is 10.6 hr).

Equipment

thorium nitrate
Geiger counter and scaler
aluminum foil
plastic container (e.g. refrigerator jar, ice-cream box)
rubber sponge
Petrie dish, watch glass, etc.

Chapter 22 Schedule Blocks

Chapter 22: Isotopes

Read 22.1 – 22.3

Isotopes

Read 22.6 – 22.8

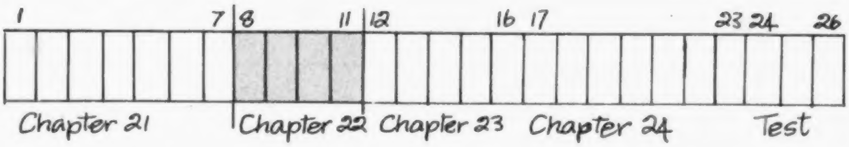
Nuclides

Read 22.4 – 22.5

Mass
Spectrograph
separation

Review

Test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Chapter 22 Resource Chart

Text	Schedule	Problems			Experiments and Teacher Demonstration
		Easy		Hard	
22.1 The concept of isotopes		1			
22.2 Transformation rules			2		
22.3 Direct evidence for isotopes of lead					
22.4 Positive rays					
22.5 Separatirig isotopes			3	4	D61 Mass spectrograph D62 Aston analogue
22.6 A usefull notation for nuclides and nuclear reactions		5	6 7 8		
22.7 The stable isotopes of the elements and their relative abundences.				9	
22.8 Atomic masses		10 11			

F50 Long time intervals

T44 Radioactive Displacement rules

L6-2 Thomson's positive ray parabolas

F51 Isotopes
T45 Mass spectrograph
L6-3 Aston's mass spectrograph
T46 Chart of the nuclides

Chapter 23 Schedule Blocks

Chapter 23: Probing the Nucleus

Read 23.1–23.3

Proton–electron hypothesis

Read 23.4

Chadwick and problem seminar

Read 23.5–23.6

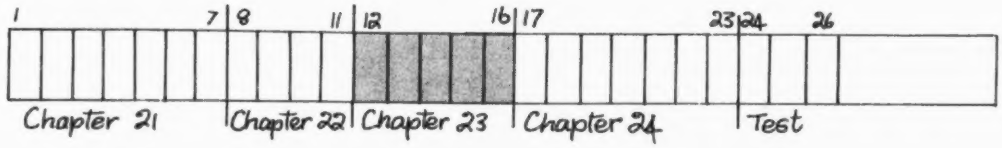
Proton-electron hypothesis
vs
Proton-neutron theory

Read 23.7–23.9

Nuclear reactions

Review

Test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Chapter 23 Resources Chart

Text	Schedule	Problems Easy		Hard	Experiments and Teacher Demonstration
23.1 The problem of the composition and structure of the atomic nucleus.			1		
23.2 The proton-electron hypothesis of nuclear structure		2			
23.3 The discovery of artificial transmutations.		3			
23.4 The discovery of the neutron		4 5	6		
23.5 The proton-neutron theory of the composition of atomic nuclei.		8 9			
23.6 The neutrino					
23.7 The need for particle accelerators				7	
23.8 Nuclear reactions		11	10		
23.9 Artificially induced radioactivity		12	13		

Chapter 23 Resource Chart

Transparencies, Loops, Films, Reader, Programmed Instruction	Student Activities
L49 Collisions with an unknown object R5 The tracks of nuclear particles R6 The spark chamber	
R3 Some personal notes on the search for the neutron R16 The fall of parity R17 Can time go backward?	Neutron detection Problem analogue (Chadwick's problem)
R11 Models of the nucleus	
R4 Antiprotons	
F52 The linear accelerator R7 The evolution of the cyclotron R8 The cyclotron as seen by… R9 Cern	
T47 Nuclear equations L6-4 Nuclear reactions R10 Mr. Tomkins Tastes a Japanese Meal	
F53 Positron-electron annihilation	

Chapter 24 : Nuclear Energy, Nuclear Forces

Read 24.1 – 24.3

Nuclear binding

Read 24.4 – 24.5

Fission and problem seminar

Read 24.6 – 24.7

Fission (continued)

Read 24.8 – 24.10

Fusion and problem seminar

Read 24.11 – 24.12

Models

Read 24.13, E48*

Radioactive tracers

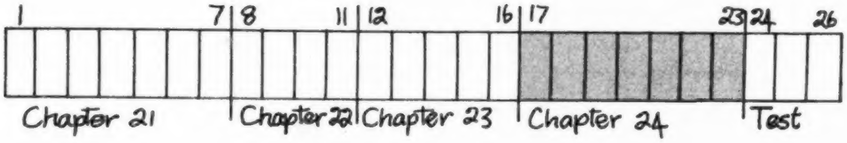
Review

Chapter test

Unit review

Unit test

Go over unit test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Chapter 24
Test

Chapter 24 Resources Chart

Text		Schedule	Problems			Experiments and Teacher Demonstration
			Easy		Hard	
24.1	Conservation of energy in nuclear reactions					
24.2	The energy of nuclear binding					
24.3	Stability and binding energy		1 2			
24.4	The mass energy balance in nuclear reactions			3 4 6	5	
24.5	Nuclear fission: discovery			7 8 9		
24.6	Nuclear fission: Controlling chain reactions.			10		
24.7	Nuclear fission: Large scale energy release and some of its consequences					
24.8	Nuclear fusion					
24.9	Fusion reaction in stars		11 12	14 15 16	13	
24.10	The strength of nuclear forces					
24.11	The liquid drop nuclear model			17 18		
24.12	The shell model					
24.13	Biological and medical applications of nuclear physics					E 48* Radioactive tracers

Chapter 24 Resources Chart

Transparencies, Loops, Films, Reader, Programmed Instruction	Student Activities
R15 Conservation laws 1 One scientist and his view of science	
T48 Binding energy curves	
F54 Fission L6-5 Critical size R13 Success	Two models of a chain reaction
4 The nuclear energy revolution R18 A report to the secretary of war R19 Twentieth birthday of the atomic age R20 Calling all stars	
	More information on nuclear fission and fusion
R12 Power from the stars R23 The development of the space-time view of quantum electrodynamics	
R24 Physics and mathematics	
R11 Models of the nucleus	
R21 Tasks for a world without war	Peaceful uses of radioactivity

E48*: Radioactive Tracers

Although one simple autoradiograph experiment is described, the intent of this exercise is to encourage students to design their own tracer experiments, for which a bibliography of source material is given. The teacher needs to plan ahead carefully so that the radioisotopes are ordered in time and so that the necessary equipment for handling them is on hand.

Equipment

A. For doing the autoradiograph experiment described here:

Polaroid film types 57, 4" x 5" OR
No-Screen x-ray film, 5" x 7" sheets
Polaroid camera back or developing roller OR x-ray developer and fixer
radioactive object—radioisotope, lump of radioactive ore, luminous watchdial with crystal removed

Brief Answers to Unit 6 Study Guide

Chapter 21

21.1 (a) The radioactivity of thorium was proportional to the amount of thorium.
(b) new radioactive elements polonium and radium

21.2 (a) 1.2×10^{-13} joule
(b) 0.75 MeV

21.3 (a) 5.7×10^{-2} m
(b) 420 m
(c) 7350:1

21.4 (a) 1.0×10^{4} N/coul
(b) 1.0×10^{3} volts
(c) undeflected

21.5 (a) γ (f) α
(b) α (g) β
(c) α (h) α
(d) γ (i) α
(e) γ (j) β

21.6 (a) Radium decayed into radon (a gas) which decays into radium A which is deposited on nearby objects.
(b) The residue contained daughters of high activity (short half-life).
(c) The uranium compound continually decayed into more active daughters, but daughters in the residue were not replaced as they decayed.

21.7 (a) 1/2
(b) 3/4
(c) Assume the products of decay were not themselves radioactive.

21.8 (a) graph
(b) 8.31×10^{19} atoms
(c) 5.0×10^{20} atoms

21.9 (a) 5.7×10^{-13} joules/disintegration
(b) 45 watts

21.10 3.70×10^{5} disintegrations/sec

21.11 5.0×10^{-3}/min
5×10^{3} atoms/min
Yes

21.12 10% of the 90% or 9% of the original.

Chapter 22

22.1 Isotopes of an element have the same z.

22.2 Determine if its chemical properties are unique.

22.3 (a) The lighter particles would diffuse away from the liquid surface more rapidly after evaporation, hence fewer of them would re-enter the liquid.
(b) The hydrogen isotopes have the largest ratio of isotopic masses (2:1) and hence the largest ratio of speeds ($1:\sqrt{2}$).

22.4 (a) 0.054 m
(b) 5.64 m
(c) 0.005 m

22.5 (a) ${}_{82}Pb^{212} \qquad {}_{83}Bi^{212} + {}_{-1}e^{0}$
(b) ${}_{83}Bi^{212} \qquad {}_{84}Po^{212} + {}_{-1}e^{0}$
(c) ${}_{84}Po^{212} \qquad {}_{82}Pb^{208} + {}_{2}He^{4}$

22.6 chart, the end product being ${}_{82}Pb^{207}$.

22.7 diagram, ending with ${}_{82}Pb^{208}$. The alternatives are in the mode of decay of ${}_{84}Po^{216}$ and ${}_{83}Bi^{216}$

22.8 decay diagram, the modes of decay are β, α, α, β, α, α.

22.9 4000 years
25000 years

22.10 (a) 12.011 amu
(b) 6.941 amu
(c) 207.2 amu

22.11 4.0015 amu

Chapter 23

23.1 235 is not divisible by 4.

23.2 235 protons
143 electrons

23.3 (a) ${}_{6}C^{13}$ (b) ${}_{12}Mg^{26}$ (c) ${}_{14}Si^{30}$
(d) ${}_{16}S^{32}$ (e) ${}_{19}K^{37}$

23.4 (a) ${}_{2}He^{3}$ (b) ${}_{3}Li^{6}$
(c) ${}_{4}Be^{8}$ (d) ${}_{0}n^{1}$

23.5 (a) γ (b) Al^{28}
(c) Mg^{24} (d) Mg^{25}
The same nuclide bombarded by different particles will yield different products.

23.6 Nitrogen nuclei are an order of magnitude more massive than hydrogen nuclei.

23.7 1.24 amu
7.8%

23.8 table

22.9 (a) 78 (b) 79 (c) 80

23.10 The missing product nuclide in each case is the same: ${}_{11}Na^{24}$.

23.11 description

23.12 explanation

23.13 explanation

Study Guide
Brief Answers

Chapter 24

24.1 4.95 MeV

24.2 7.07 MeV/nucleon

24.3 opposite directions,
each with KE of 8.65 MeV

24.4 absorbed,
1.19 MeV

24.5 0.56 MeV

24.6 8.61 MeV

24.7 neutron capture,
β-decay
β-decay

24.8 U^{235}: 1790 MeV
Ba^{141}: 1180 MeV
Kr^{92}: 800 MeV

24.9 208 MeV

24.10 least loss—spherical
most loss—flat sheet

24.11 very high KE protons required

24.12 high enough temperatures result
from the collapse

24.13 "proof"

24.14 (a) 4.33×10^9 kg/sec
(b) 5.23×10^{23} horsepower

24.15 (1) $_7N^{13}$ (4) $_7N^{14}$
(2) $_7N^{13}$ (5) $_7N^{15}$
(3) $_7N^{14}$ (6) $_7N^{15}$

24.16 released,
1.59 MeV

24.17 Yes, because the excitation energy
is greater than the activation
energy.

24.18 Yes

Solutions to Chapter 21 Study Guide

21.1

If the Curies had relied only on photographic techniques for detecting radioactivity they would have been unlikely to discover

a) that the intensity of radiation from thorium was directly proportional to the amount of thorium in the sample.
b) two other radioactive elements (polonium and radium) in pitchblende.

The use of the sensitive electrometer invented by Pierre Curie yielded quantitative information that greatly facilitated the above discoveries.

21.2

a) The energy of a photon

$$E = hf = \frac{hc}{\lambda}$$

$$= \frac{6.6 \times 10^{-34}\ \text{joule}\cdot\text{sec} \times 3 \times 10^{8}\ \text{m/sec}}{0.016 \times 10^{-10}\ \text{m}}$$

$$= 1.2 \times 10^{-13}\ \text{joule}$$

b) Since 1 eV = 1.6×10^{-19} joule,

the energy in (a) is $\dfrac{1.2 \times 10^{-13}\ \text{joule}}{1.6 \times 10^{-19}\ \text{joule/eV}}$

$$= 0.75 \times 10^{6}\ \text{eV}$$

or 0.75 MeV.

21.3

a) The magnetic force is a centripetal force;

$$Bqv = \frac{mv^2}{R},\ \text{so}\ R = \frac{mv}{Bq}$$

$$R = \frac{9.1 \times 10^{-31}\text{kg} \times 1.0 \times 10^{7}\text{m/sec}}{1.0 \times 10^{-3}\text{N/amp}\cdot\text{m} \times 1.6 \times 10^{-19}\text{coul}}$$

$$= 5.7 \times 10^{-2}\text{m}$$

b) In part (a) it is seen that the radius of curvature is directly proportional to the mass of the particle; so for α particles of the same speed as the electrons, the radius of curvature

$$= 5.7 \times 10^{-2}\text{m} \times \frac{6.7 \times 10^{-27}\text{kg}}{9.1 \times 10^{-31}\text{kg}}$$

$$= 420\ \text{m}$$

c) The radius of curvature of the α particles is far larger (i.e., they are less deflected) than that of electrons. The ratio of their radii of curvature is $\dfrac{6.7 \times 10^{-27}\text{kg}}{9.1 \times 10^{-31}\text{kg}} = \dfrac{7350}{1}$

21.4

a) When the electric and magnetic forces on a charged particle are in balance,

$$qE = Bqv,\ \text{so}\ E = Bv$$

$$E = 1.0 \times 10^{-3}\frac{\text{N}}{\text{amp}\cdot\text{m}} \times 1.0 \times 10^{7}\frac{\text{m}}{\text{sec}}$$

$$= 1.0 \times 10^{4}\frac{\text{N}}{\text{amp}\cdot\text{sec}} = 1.0 \times 10^{4}\ \frac{\text{N}}{\text{coul}}.$$

b) The electric field strength is the ratio of the voltage to the plate separation; $E = \frac{V}{d}$,

so $V = Ed = 1.0 \times 10^{4}\ \dfrac{\text{N}}{\text{coul}} \times 0.10\ \text{m}$

$$= 1.0 \times 10^{3}\ \frac{\text{joules}}{\text{coul}} = 1.0 \times 10^{3}\ \text{volts}.$$

c) As can be seen in part (a), the condition for balance does not involve the charge of the particle but only the speed; thus the α particles will pass through the crossed fields undeflected.

21.5

a) γ
b) α
c) α
d) γ
e) γ
f) α*
g) β
h) α
i) α
j) β

*The radius of curvature of the γ is infinite; therefore one could put γ for this answer.

21.6

a) The radium decays into radon, a gas ("emanation"), which diffuses into the surrounding atmosphere. Some atoms of radon will decay immediately or nearly immediately to Radium A, a solid, which will be deposited on nearby objects. Since Radium A and its daughters are radioactive, the ordinary objects would appear to have acquired radioactivity. Another possibility is that the initially nonradioactive substances might be transmuted into unstable isotopes by radiation from the radium compound.

b) The uranium compound and the daughters which resulted from its decay were separated into two parts—the uranium and the daughters. Since the daughters have a shorter half-life than the uranium, the activity of the part containing the daughters would be greater.

c) The decay of the uranium would gradually lead to a buildup of the daughters in the series. Since the daughters have shorter half-lives the activity would be greater. On the other hand, some of the daughters would have, in the interval, reached Ra G (stable lead) so a smaller proportion of atoms would be radioactive. A poor analogy might be with balls dropped periodically down a long and irregular flight of stairs. We notice the bounces as the ball goes from one step to another. If the rate at which balls are let loose at the top is slow (the half-life is long), the number of bounces on an initially empty staircase (daughters separated initially) will slowly build up. On the other hand, if the source at the top is cut off (no more uranium) more and more balls will reach the bottom of the staircase without replacement so the total number of bounces will slowly decrease. That only several months are required to approach equilibrium is surprising since some of the other half-lives are quite long.

21.7

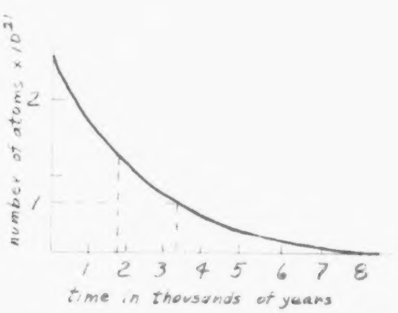
a) Since the rate of emission is proportional to the fraction of the sample remaining, one-half of the original number will remain after 25 hours.

b) Since one-quarter of the original number will remain after 50 hours, three-quarters will have disintegrated.

c) We have assumed that the radioactive substance did not decay into daughter products that are unstable and contribute to the β-emission. To check this possibility one would have to separate the daughter products by chemical means and determine whether or not they were radioactive.

21.8

a)



b) 8000 years = 5 half-lives

$$N_{8000\text{ years}} = N_o\left(\frac{1}{2}\right)^5 = 2.66 \times 10^{21}\left(\frac{1}{32}\right)$$

$$= .0831 \times 10^{21}$$

$$= 8.31 \times 10^{19} \text{ atoms.}$$

c) $N_{4000\text{ years}} \approx .5 \times 10^{21}$

$$= 5.0 \times 10^{20} \text{ atoms.}$$

21.9

a) The rate of energy release is 360 watts, or 360 joules/sec. This corresponds to 17,000 curies × 3.70×10^{10} disintegrations, = 6.3×10^{14} disintegrations.

The energy release per disintegration is

$$\frac{360 \text{ joules/sec}}{6.3 \times 10^{14} \text{ disintegrations/sec}}$$

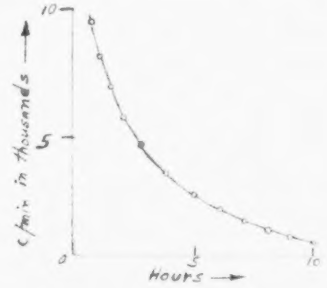
$$= 5.7 \times 10^{-13} \text{joule/disintegration.}$$

b) After 15 years, or 3 half-lives, the rate of heat production will be 360 watts $\times \left(\frac{1}{2}\right)^3$ = 45 watts.

21.10

The activity is 10 microcuries, or 10×10^{-6} curies, which is 10^{-5} curies × 3.70×10^{10} disintegrations per curie per second = 3.70×10^5 disintegrations/sec.

21.11



The half-life, T, can be obtained from a graph of the data (see above curve; also below). For example, it takes about 2.3 hours (138 min) for the counting rate to drop from 8000 counts/min to 4000 counts/min. To drop from 4000 counts/min to 2000 counts/min requires about 2.3 hours (138 min). To drop from 2000 counts/min to 1000 counts/min again requires about 2.3 hours (138 min). Thus the half-life appears to be constant at about 138 min.

The decay rate can be computed from

$$\lambda T = 0.693$$

$$\lambda = \frac{0.693}{138} = 5.0 \times 10^{-3}/\text{min.}$$

Since λ is the fraction of any sample of atoms that decay per minute, a sample of 10^6 atoms will have 5.0×10^{-3}/min × 10^6 = 5×10^3 atoms decaying each minute.

Yes, the number of atoms decaying/per minute for every 10^6 atoms in the sample does remain constant.

21.12

If 10% of the sample decays in the first 10 years, 10% of the remaining 90% decays in the next 10 years: 10% of 90% is 9% of the original amount.

Solutions to Chapter 22 Study Guide

22.1

The chemical properties of an element are determined by its electron configuration, which in turn is determined by the atomic number Z. The isotopes of an element have the same Z and hence the same chemical properties.

22.2

If the apparently new element had chemical properties different from those of any known element, then one could be certain that the element deserved a separate place in the periodic table. If, on the other hand, it was found to have chemical properties identical to those of a known element (although having a slightly different mass than the known element) then it could be regarded as an isotope of the known element.

22.3

a) Although the rate of escape from the surface would be the same for both, (escape requires a certain amount of work against cohesive forces, and so depends on KE, not speed per sec) the lighter and hence faster particles would diffuse away from the surface more rapidly after escape, and so have a lower probability of re-entering the surface.

b) The hydrogen isotopes have the largest ratio of isotopic masses (2:1) and hence the largest ratio of speeds ($1:\sqrt{2}$). Separation of the hydrogen isotopes by evaporation therefore proceeds more rapidly than separation of isotopes of other elements.

22.4

The magnetic force is the centripetal force, so $Bqv = \frac{mv^2}{R}$, thus

$$R = \frac{mv}{Bq}, \text{ and so } R \propto m.$$

$$\frac{R_{35}}{R_{37}} = \frac{\text{Diam}_{35}}{\text{Diam}_{37}} = \frac{m_{35}}{m_{37}}$$

$$\frac{D_{35}}{1.000 \text{ m}} = \frac{34.97}{36.97} \text{ (See Table 22.1)}$$

$$D_{35} = 0.9460 \times 1.000 \text{ m} = 0.9460 \text{ m}.$$

Therefore, the separation is

$$D_{37} - D_{35} = 1.000 \text{ m} - 0.9460 \text{ m}$$
$$= 0.054 \text{ m}$$
$$\text{or } 5.4 \text{ cm}.$$

b) $D_{208} = \frac{208.0}{36.97} \times 1.000 \text{ m} = 5.640 \text{ m}$

c) $\frac{D_{207}}{D_{208}} = \frac{m_{207}}{m_{208}}$

$$D_{207} = \frac{207.0}{208.0} \times 1.000 \text{ m}$$
$$= 0.9950 \text{ m}$$

The separation is therefore 1.000 m - 0.9950 m = 0.005 m. Note that if the division is to be done on a slide rule, a more accurate answer can be obtained as follows by using the fact that $\frac{1}{1+x} = 1 - x$ when $x \ll 1$.

The separation is $1.000 \text{ m} - \frac{207.8}{208.0} \times 1.000 \text{ m}$

$$= 1.000 \text{ m} - \frac{1}{\frac{208.0}{207.0}} \text{ m}$$

$$= 1.000 \text{ m} - \frac{1}{1.000 + \frac{1.0}{207.0}} \text{ m}$$

$$= 1.000 \text{ m} - (1.000 - \frac{1.0}{207.0}) \text{ m}$$

$= \frac{1.0}{207.0}$ m; this division can be accurately done on a slide rule to yield 0.0048 m.

22.5

a) ${}_{82}\text{Pb}^{212} \longrightarrow {}_{83}\text{Bi}^{212} + {}_{-1}e^{0}$

(Since the mass number didn't change, the transmutation was due to beta decay.)

b) ${}_{83}\text{Bi}^{212} \longrightarrow {}_{84}\text{Po}^{212} + {}_{-1}e^{0}$

In a beta decay, the atomic number increases by one but the mass number remains unchanged. The product nucleus here then has Z = 84 and A = 212. Reference to a list of elements or periodic table, such as are shown on the preceding page, shows that the element with Z = 84 is polonium.

c) ${}_{92}\text{Po}^{212} \longrightarrow {}_{82}\text{Pb}^{208} + {}_{2}\text{He}^{4}$

The atomic number of lead is 82, the atomic number and mass number of the initial nucleus must therefore be 84 and 212. As was seen in part (b), the element is polonium.

22.6

Actinium Series

New Symbol	Decay Made
${}_{92}U^{235}$	α $({}_2He^4)$
${}_{90}Th^{231}$	β $({}_{-1}e^0)$
${}_{91}Pa^{231}$	α
${}_{89}Ac^{227}$	β
${}_{90}Th^{227}$	α
${}_{88}Ra^{223}$	α
${}_{86}Rn^{219}$	α
${}_{84}Po^{215}$	α
${}_{82}Pb^{211}$	β
${}_{83}Bi^{211}$	α
${}_{81}Tl^{207}$	β
${}_{82}Pb^{207}$	stable

22.7

$${}_{90}Th^{232} \xrightarrow{\alpha} {}_{88}Ra^{228} \xrightarrow{\beta} {}_{89}Ac^{228} \xrightarrow{\beta}$$

$${}_{90}Th^{228} \xrightarrow{\alpha} {}_{88}Ra^{224} \xrightarrow{\alpha} {}_{86}Rn^{220} \xrightarrow{\alpha}$$

$$\begin{tikzcd} & {}_{82}Pb^{212} \arrow[dr, "\beta"] & & {}_{81}Tl^{208} \arrow[dr, "\beta"] & \\ {}_{84}Po^{216} \arrow[ur, "\alpha"] \arrow[dr, "\beta"'] & & {}_{83}Bi^{212} \arrow[ur, "\alpha"] \arrow[dr, "\beta"'] & & {}_{82}Pb^{208}. \\ & {}_{85}At^{216} \arrow[ur, "\alpha"'] & & {}_{84}Po^{212} \arrow[ur, "\alpha"'] & \end{tikzcd}$$

(The decay route through ${}_{82}Pb^{212}$ is much more common than through ${}_{85}At^{216}$. The other case of branching is unusual in that the two decay routes are both common; ${}_{81}Tl^{208}$ is formed 33.7% of the time and ${}_{84}Po^{212}$ is formed 66.7% of the time.)

22.8

$${}_{94}Pu^{241} \xrightarrow{\beta} {}_{95}Am^{241} \xrightarrow{\alpha} {}_{93}Np^{237} \xrightarrow{\alpha} {}_{91}Pa^{233}$$

$${}_{92}U^{233} \xrightarrow{\alpha} {}_{90}Th^{229} \xrightarrow{\alpha} {}_{88}Ra^{225}$$

22.9

The percentage of the original activity at the time of measurement is $\frac{9.2}{15.3} \times 100\% = 60\%$.

Referring to the radioactivity decay curve on p. 24, it can be seen that 60% corresponds to a time of approximately 0.7T or 0.7 × 5760 yr, which is about 4000 years.

An activity of 1.0 beta emissions per minute per gram of carbon is $\frac{1.0}{15.3} \times 100\% = 6.5\%$ of the original activity. From the curve on p. 24, this activity is seen to correspond to a time of nearly 4T, or 25,000 years.

22.10

The average atomic mass is the sum of the products of relative abundance and isotopic mass

a) For carbon, the average mass

$$A = 0.9889 \times 12.000 + 0.0111 \times 13.00$$

$$= 11.867 + 0.144$$

$$= 12.011 \text{ amu}$$ (five significant digits are justified because 0.9889 is accurate to 1 part in 10,000).

b) For lithium, the average mass

$$A = 0.0742 \times 6.015 + 0.9258 \times 7.016$$

$$= 0.446 + 6.495$$

$$= 6.941 \text{ amu}$$

c) For lead, the average mass is

$$A = 0.0148 \times 203.97 + 0.236 \times 205.97$$

$$+ 0.226 \times 206.98 + 0.523 \times 207.98$$

$$= 3.02 + 48.6 + 46.8 + 108.8$$

$$= 207.2 \text{ amu}$$

22.11

The mass of the alpha particle can be found by subtracting the mass of two electrons from the mass of the helium atom:

$$m_\alpha = m_{HE} - 2\ m_e$$

$$= 4.00260 \text{ amu} - 0.0011 \text{ amu}$$

$$= 4.0015 \text{ amu.}$$

Note—the actual mass is slightly larger than the amount obtained by simple subtraction because of the transformation of binding energy to mass. The difference is negligible though, because the mass equivalent of the binding energy of an electron is of the order of 10^{-9} amu.

Solutions for Chapter 23 Study Guide

23.1

Since the mass number of ${}_{92}U^{235}$ is not exactly divisible by 4 (the mass of an α particle) it is hard to see how a nucleus could be made up of only electrons and alpha particles. Also, by the uncertainty principle, the electrons could not exist in the nucleus.

23.2

According to the proton-electron hypothesis, the nucleus represented by ${}_{92}U^{235}$ would be composed of 235 protons; 235 - 92 = 143 electrons.

23.3

(a) $${}_{5}B^{10} + {}_{2}He^{4} \longrightarrow {}_{6}C^{13} + {}_{1}H^{1}$$

Since mass number is conserved, 4 + 10 = 14, 14 - 1 = 13. Since nuclear charge is conserved, 5 + 2 = 7, 7 - 1 = 6. So Z = 6, which is the atomic number of carbon.

(b) $${}_{11}Na^{23} + {}_{2}He^{4} \longrightarrow {}_{12}Mg^{26} + {}_{1}H^{1}$$

For mass number; 23 + 4 = 27, 27 - 1 = 26.
For nuclear charge; 11 + 2 = 13, 13 - 1 = 12.
Z = 12 is the atomic number of magnesium.

(c) $${}_{13}Al^{27} + {}_{2}He^{4} \longrightarrow {}_{14}Si^{30} + {}_{1}H^{1}$$

For mass number; 27 + 4 = 31, 31 - 1 = 30.
For nuclear charge; 13 + 2 = 15, 15 - 1 = 14.
Z = 14 is the atomic number of silicon.

(d) $${}_{16}S^{32} + {}_{2}He^{4} \longrightarrow {}_{17}Cl^{35} + {}_{1}H^{1}$$

For mass number; 35 + 1 = 36, 36 - 4 = 32.
For nuclear charge; 17 + 1 = 18, 18 - 2 = 16.
Z = 16 is the atomic number of sulfur.

(e) $${}_{19}K^{37} + {}_{2}He^{4} \longrightarrow {}_{20}Ca^{42} + {}_{1}H^{1}$$

For mass number; 42 + 1 = 43, 43 - 4 = 39.
For nuclear charge; 20 + 1 = 21, 21 - 2 = 19.
Z = 19 is the atomic number of potassium.

23.4

(a) $${}_{3}Li^{6} + {}_{1}H^{1} \longrightarrow {}_{2}He^{4} + {}_{2}He^{3}$$

mass number: 6 + 1 = 7; 7 - 4 = 3

nuclear charge: 3 + 1 = 4; 4 - 2 = 2

(${}_{2}He^{3}$ is a rare isotope of helium, natural abundance = 0.00013%)

(b) $${}_{4}Be^{9} + {}_{1}H^{1} \longrightarrow {}_{2}He^{4} + {}_{3}Li^{6}$$

(c) $${}_{4}Be^{9} + {}_{1}H^{1} \longrightarrow {}_{4}Be^{8} + {}_{1}H^{2}$$

(d) $${}_{5}Be^{11} + {}_{2}He^{4} \longrightarrow {}_{7}N^{14} + {}_{0}n^{1}$$

23.5

(a) $$Al^{27} + {}_{0}n^{1} \longrightarrow Al^{28} + \gamma$$

Since Z does not change ($Al \longrightarrow Al$) and since mass numbers already balance, only a γ ray (no charge, no mass) can result.

(b) $$Al^{27} + {}_{1}H^{2} \longrightarrow {}_{1}H^{1} + Al^{28}$$

Since $Z_{Al} + 1 = Z_{Al} + 1$, the resulting nucleus must be aluminum. Total mass number on the left side is 29 (27 + 2) = total mass number on right side. So $A_{Al} + 1 = 29$ and we have Al^{28}.

(c) $$Al^{27} + {}_{1}H^{1} \longrightarrow {}_{2}He^{4} + Mg^{24}$$

Since the particle input on the left has charge 1 and the particle output on the right has charge 2, the nucleus on the right has one less positive charge than the nucleus on the left: move one place toward hydrogen in the periodic table. The nucleus must be magnesium.

Alternatively, $Z_{Al} = 13$ so 13 + 1 = 14; 14 - 2 = 12 and $Z_{Mg} = 12$.

For mass number: 27 + 1 = 28, 28 - 4 = 24

(d) $$Al^{27} + {}_{1}H^{2} \longrightarrow {}_{2}He^{4} + Mg^{25}$$

By the reasoning of (c), the nucleus is magnesium.

Mass number: 27 + 2 = 29, 29 - 4 = 25

The same nuclide bombarded by different particles will yield different products.

23.6

Since nitrogen nuclei are about 14 times more massive than neutrons, if the neutron were to hit the nitrogen nucleus and stop dead in its track, the nitrogen nucleus would have a velocity of only 1/14 × the original velocity of the neutron v_n. Actually, the neutron rebounds somewhat, but its velocity of rebound cannot be greater than its initial velocity or energy would not be conserved. Thus the momentum given the nitrogen nucleus must be less than twice the original neutron momentum, and the nitrogen nucleus must have a velocity less than 2(1/14 of the original neutron velocity). We can see then, without calculating the actual velocity of the nitrogen nucleus, that it must have been between 1/14 and 1/7 the original neutron velocity (i.e., an order of magnitude less). But since the neutron and proton have nearly the same mass, a complete transfer of momentum from neutron to proton would give the proton very nearly the same velocity as the original velocity of the neutron. Thus, the nitrogen nucleus will have a velocity an order of magnitude less than the proton's velocity.

23.7

From page 61,

$$\frac{v_p}{v_N} = \frac{m_N + m_n}{m_p + m_n}.$$ Substituting for known masses and speeds:

$$\frac{m_n + 14}{m_n + 1} = \frac{3.2 \times 10^9 \text{ cm/sec}}{4.7 \times 10^8 \text{ cm/sec}} = 6.8$$

so

$$m_n + 14 = 6.8\ (m_n + 1)$$

$$5.8\ m_n = 14 - 6.8 = 7.2$$

$$m_n = 1.24 \text{ amu}$$

Difference in mass: 1.24 - 1.16 = 0.08 amu.

Percent difference

$$= \frac{0.08}{1.16} = 6.9\%$$

Thus, a difference of measurement of 3% is multiplied in the calculation to a difference of 6.9%.

23.8

	A	Z	protons	neutrons
H^1	1	1	1	0
H^2	2	1	1	1
He^4	4	2	2	2
Li^7	7	3	3	4
C^{13}	13	6	6	7
U^{238}	238	92	92	146
Th^{234}	234	90	90	144
Th^{230}	230	90	90	140
Pb^{214}	214	82	82	132
Pb^{206}	206	82	82	124

23.9

(a) 78 (b) 79 (c) 80

23.10

(a) $${}_{11}Na^{23} + {}_{1}H^{2} \longrightarrow {}_{1}H^{1} + {}_{11}Na^{24}$$

For method of solution see SG 23.3.

(b) $${}_{11}Na^{23} + {}_{0}n^{1} \longrightarrow \gamma + {}_{11}Na^{24}$$

(c) $${}_{12}Mg^{24} + {}_{0}n^{1} \longrightarrow {}_{1}H^{1} + {}_{11}Na^{24}$$

(d) $${}_{12}Mg^{26} + {}_{1}H^{2} \longrightarrow {}_{2}He^{4} + {}_{11}Na^{24}$$

Notice that the nuclide ${}_{11}Na^{24}$ can be produced in at least four ways. Of course, the reactions noted are not unique. When bombarding ${}_{11}Na^{23}$ with neutrons, for example, the major product varies with the neutron energy and, even with single-energy neutrons, more than one type of product may result. (The target, after all, contains many more than one nucleus of ${}_{11}Na^{23}$.)

23.11

When a target of the aluminum nuclide with mass number 27 is bombarded by neutrons, the neutrons react with the aluminum to produce a magnesium nuclide with mass number 27 and an ejected proton. The magnesium nuclide is radioactive, undergoing beta decay, accompanied by emission of a gamma ray and an anti-neutrino. The half-life of the artificially radioactive Mg nucleus is 9.5 minutes.

23.12

Assume that the tracks originate at the point marked A: the law of the conservation of momentum requires that the vector sum of the momenta of the two particles be equal to the momentum of the neutral particle that 'exploded' at point A.

A similar argument holds if the tracks terminate at A, except that in this case the neutral particle (which leaves no track) goes off in the direction determined by the vector sum of the momenta of the particles that combined at A.

23.13

The existence of artificially radioactive nuclides simply provided much more data on unstable (radioactive) nuclides. There are only 54 naturally occurring radioactive nuclides, i.e., only 54 test cases for theories of nuclear stability. Most of these are heavy nuclides. The manufacture of 1200 artificial nuclides which span the entire spectrum of mass number and charge made possible far more sensitive tests of theoretical prediction.

Solutions to Chapter 24 Study Guide

24.1

$$C^{12} + n \longrightarrow C^{13}$$

The mass of the neutron added is 1.008665 amu, whereas the mass of C^{13} is only greater than that of C^{12} by 1.003354 amu. The discrepancy in mass (often called the "mass defect") of 0.005311 amu is equivalent to 0.005311 amu × 931 MeV/amu = 4.95 MeV, and represents the binding energy of the neutron.

24.2

The sum of the individual masses of the 2 protons, 2 neutrons and 2 electrons comprising the helium atom is 2 × (1.007276 + 1.008665 + 0.000549) amu = 4.03298 amu. Since the atomic mass is only 4.00260 amu, there is a mass difference of 0.03038 amu, which is equivalent to 0.03038 × 931 MeV/ amu = 28.3 MeV. Therefore, the average binding energy is 28.3 MeV/4 nucleons = 7.07 MeV/nucleon.

(The binding energy of the two electrons was ignored—it is only 13 eV per electron.)

24.3

By the law of the conservation of momentum the two α particles will fly off with identical speeds but in opposite directions. Their total KE is calculated on p. 87 to be 17.3 MeV, thus they would each have a KE of 8.65 MeV.

24.4

The total atomic mass of the reactants is 14.003074 amu + 4.002604 amu = 18.005678 amu. The total atomic mass of the products is 16.999134 amu + 1.007825 amu = 18.006959 amu. Since the products have a greater total mass than have the reactants, energy must have been absorbed in the reaction.

The mass difference is 0.001281 amu, which is equivalent to 0.001281 amu × 931 MeV/amu = 1.19 MeV. Thus,

$$_7N^{14} + _2He^4 + 1.19\ \text{MeV} \longrightarrow {}_8O^{17} + {}_1H^1.$$

24.5

As calculated in the prededing question, 1.19 MeV is required to promote the reaction. If we subtract this from the KE of the α particles, the amount of energy remaining will represent the total KE of the reactants (we assume that the N^{14} target is stationary). Thus, 7.68 MeV - 1.19 MeV = 6.49 MeV is the total KE of the reactants. The "recoil" energy of the O^{17} nucleus is then the difference between 6.49 MeV and 5.93 MeV, or 0.56 MeV.

24.6

The total atomic mass of the reactants is 14.003074 amu + 2.014102 amu = 16.017176 amu. The total atomic mass of the products is 15.000108 amu + 1.007825 amu = 16.007933 amu. The mass difference (mass defect) is thus 16.017176 amu - 16.007933 amu = 0.09243 amu. The energy liberated is 0.09243 amu × 931 MeV/amu = 8.61 MeV.

24.7

We consider three successive steps.

1. Addition of a neutron. This changes the total number of nucleons by one, but does not change the charge number.

$$_{90}Th^{232} + {}_0n^1 \longrightarrow {}_{90}Th^{233}$$

(neutron capture).

2. β-decay. The total number of nucleons remains the same. A neutron changes to a proton with β-decay, i.e., the emission of an electron. This enhances the charge number by 1.

$$_{90}Th^{233} \longrightarrow {}_{91}Pa^{233} + {}_{-1}e^0.$$

3. Another β-decay gives the final transition to $_{92}U^{233}$.

$$_{91}Pa^{233} \longrightarrow {}_{92}U^{233} + {}_{-1}e^0.$$

24.8

From the figure we find approximately:

B.E. per nucleon for Ba^{141} = 8.4 MeV

B.E. per nucleon for Kr^{92} = 8.7 MeV

B.E. per nucleon for U^{235} = 7.6 MeV.

The total binding energy is found in each case by multiplying by the total number of nucleons in the nucleus. Thus we have

total B.E. of Ba^{141}

= 8.4 × 141 = 1180 MeV

total B.E. of Kr^{92}

= 8.7 × 92 = 800 MeV

sum = 1980 MeV.

total B.E. of U^{235}

= 1790 MeV.

The energy released in the reaction is equal to the difference of the total binding energy of the products and the total binding energy of the incident particles, i.e.,

= (1980 - 1790) MeV

= 190 MeV

≈ 200 MeV.

24.9

U^{235}: 235.04393 amu

n^1: 1.00867 amu

sum = 236.05260 amu

La^{139}: 138.9061 amu

Mo^{95} : 94.9057 amu

2 n^1: 2.0173 amu

sum = 235.8291 amu

mass defect = 0.2235 amu

Binding energy = 0.2235 amu × 931 MeV/amu = 208 MeV.

24.10

A given mass of fissionable material will lose the least number of neutrons through its surface if it is spherical in shape. Any other shape would mean a larger surface area and hence a larger loss of neutrons.

The neutron loss would be greatest if the material were formed into a thin flat sheet; the thinner the sheet, the larger the surface area and neutron loss.

24.11

The high temperatures are required for fusion to commence because the kinetic energies of the protons must be great enough to overcome the electrical repulsion between them.

24.12

As the vast clouds of hydrogen collapse gravitationally, the gravitational potential energy of the particles is transformed into kinetic energy. Eventually the contraction results in particles of sufficient kinetic energy to initiate fusion reactions.

24.13

The net result of the proton-proton chain is given as $4\,{}_1H^1 \longrightarrow {}_2He^4 + 2\,{}_{+1}e^0$.

(Note that to be complete, we should also show 2 neutrinos on the right-hand side of the equation.) Since we are to show that the energy released per cycle is about 26 MeV, we are only interested in 2 figure accuracy. Therefore we can simply deal with atomic masses and ignore the mass of the electrons and positrons. The mass defect is then

4 (1.007825 amu) - 4.002604 amu

= 0.028696 amu. The corresponding

energy release = 0.02870 amu × 931 MeV/amu

= 26.7 MeV.

24.14

a) We can use the Einstein relation $E = \Delta mc^2$ to calculate the rate of mass loss in the sun.

$$\Delta m = \frac{E}{c^2} = \frac{3.90 \times 10^{26}\ \text{joules/sec}}{(3 \times 10^8 \text{m/sec})^2}$$

$$= 0.433 \times 10^{10}\ \text{kg/sec}$$

$$= 4.33 \times 10^9\ \text{kg/sec}$$

b) 3.90×10^{26} joules/sec is 3.90×10^{26} watts

This is equivalent to $\dfrac{3.90 \times 10^{26}\ \text{watts}}{7.46\ \text{watts/hp}}$

$= 5.23 \times 10^{23}$ horsepower.

24.15

The completed six steps of the carbon cycle are as follows

$${}_6C^{12} + {}_1H^1 \longrightarrow {}_7N^{13} + \gamma$$

$${}_7N^{13} \longrightarrow {}_6C^{13} + {}_{+1}e^0 + \nu$$

$${}_6C^{13} + {}_1H^1 \longrightarrow {}_7N^{14} + \gamma$$

$${}_7N^{14} + {}_1H^1 \longrightarrow {}_8O^{15} + \gamma$$

$${}_8O^{15} \longrightarrow {}_7N^{15} + {}_{+1}e^0 + \nu$$

$${}_7N^{15} + {}_1H^1 \longrightarrow {}_6C^{12} + {}_2He^4.$$

24.16

The total atomic mass of the reactants is 3.016030 amu + 4.002604 amu = 7.018634 amu. The mass difference is 7.018634 amu - 7.016929 amu = 0.001705 amu. Therefore, the energy released is 0.001705 amu × 931 MeV/amu = 1.59 MeV.

24.17

mass of U^{233} = 233.039498 amu

mass of n^1 = 1.008665

mass of $U^{233} + n^1$ = 234.048163

- mass of U^{234} = 234.040900

mass defect = 0.007263 amu

excitation energy ≡ 0.007263 amu × 931 MeV/amu

= 6.76 MeV, but the activation energy of U^{234} = 4.6 MeV; thus, since the excitation energy is greater than activation energy, ${}_{92}U^{233}$ is fissionable with slow neutrons.

24.18

$$
\begin{aligned}
\text{mass of } Pu^{241} &= 241.056711 \text{ amu}\\
\text{mass of } n^{1} &= \underline{1.008665}\\
\text{total mass} &= 242.065376\\
-\ \text{mass of } Pu^{242} &= \underline{242.058710}\\
\text{mass defect} &= 0.006666 \text{ amu}\\
\text{excitation energy} &\cong 0.006666 \times 931 \text{ MeV}\\
&= 6.20 \text{ MeV.}
\end{aligned}
$$

Since the activation energy is only 5.0 MeV, Pu^{241} _is_ fissionable with slow neutrons.

Prologue

In Unit 5 we have discussed a number of experimental results which led to the construction of a model for the atom. In particular we have looked at the results of spectroscopic measurements. For many years an enormous amount of spectral data were taken for many different gases; Balmer's empirical relation gave this data an order which had to be explained by postulated models. We accepted Bohr's postulates because they led to a model for the hydrogen atom from which predictions checked with the known experimental data. The Rydberg constant—originally found purely experimentally—could now actually be calculated.

This approach of constructing a model to explain the experimental data can be used for the nucleus as well as for the atom. In this Unit we shall discuss some of the experimental results of nuclear physics just as we discussed experimental results of atomic physics in Unit 5. The problems are, however, very much more difficult. While the size of the atom is of the order of 10^{-10} m, the nucleus has a diameter of the order of 10^{-14} m. The energies involved on the atomic scale were relatively low—the ionization potential of hydrogen is -13.6 eV and the work function of most materials for the photoelectric effect is only a few electron volts. X-ray energies go up to a few thousand electron volts; all of these energies can be produced without too much difficulty in the laboratory.

The energies of particles inside the nucleus are several million electron volts or higher. The production of such energies is very difficult, and requires machines which appeared only gradually. As a result of these and other difficulties we are not yet in a position to postulate a nuclear model which will explain all of our experimental results. Although the practical applications of nuclear physics have increased at a very rapid rate during the last twenty years, our understanding of the detailed structure of the nucleus and the role of the so-called fundamental particles is far from complete.

We therefore present some of the experimental facts of nuclear physics with a few possible explanations. But the end to the story—the end to Unit 6—has yet to be written.

In Unit 6 we apply a number of concepts discussed in earlier units—some of these are really threads throughout the study of physics. Our α and β particles follow the dynamics discussed in Unit 1. Conservation of energy (and mass) as well as conservation of momentum (Unit 3) are used throughout this Unit. Forces on charged particles in magnetic fields (Units 4 and 5) once again play an important role. The student should be aware that he now applies principles, already studied, to the nucleus; there are relatively few new concepts in this Unit.

Sec. 21.1 Becquerel's discovery

The story of Becquerel's discovery is an exciting one, and probably little teacher explanation will be required. It would be useful to point out examples of fluorescence, such as fluorescent lights the face of a TV tube, etc. It is also useful to emphasize that phosphorescence is similar to fluorescence, the difference being that phosphorescence involves a time delay between the absorption of radiation and the subsequent re-emission. The word phosphorescence is unfortunately also used to describe the light emitted by small marine organisms (bio-luminescence). That there are two different uses of the term is worthwhile mentioning to the students.

The discovery of radioactivity by Becquerel was a kind of serendipic result, since he was looking for something quite different when he began. The question asked on the margin of page 7 is an important one, and should not be overlooked in class discussion. This is good practice in the understanding of what is meant by "evidence," and how evidence of different kinds must be carefully sorted out by scientists. Sometimes, the leap to a general inference pays off (as in the case of modern genetics); sometimes, it leads to greater confusion.

Sec. 21.2 Other radioactive elements are discovered

Here is an opportunity to give your students a feeling for two things: 1) the tremendous progress in the technology of laboratory equipment, and 2) the ability of research to exist and succeed under the conditions of minimum technology.

You could point out to your students that the Curies worked under conditions that would repel the average graduate student in science today. Their "laboratory" was just a shed with no heat, and their equipment was far poorer than that found in most junior high school science laboratories today! Nevertheless, they were able to carry out experiments of high sophistication and to make fairly exact measurements. Since they were chemists, their approach to the job of finding the source of the mysterious

Becquerel rays was a chemical one—that is, they used the technique of reducing radium ore as far as possible, until they arrived at the non-reducible substance: radium. Though it is not too pertinent until later in the Unit, you might indicate at this point that the energies involved in the chemical processes of reduction were very, very small, compared to the energies inherent in the radioactive atoms themselves.

Since their major quantitative instrument was essentially a rather sensitive electroscope, you might refer back to the Unit on electricity to remind your students about how electroscopes work, and how they can be used as measuring instruments. You might ask: is it just sheer luck that the amount of ionization produced by a "Becquerel ray" is directly proportional to the deflection of the charged electroscope leaves?

Another interesting point about the work being done during this time on both x rays and radioactive substances was the complete lack of knowledge of the biological effects of radiation. Pierre Curie carried samples of radium in glass vials in his pocket; after his death, his skin was found to have burn marks in that area. Until the invention of better tubes—notably the Coolidge tube—x-ray photos were made with very long exposures without any thought about the damage caused to cell structure. Even as late as the 1940's and early '50's, there were x-ray machines (fluoroscopes) in shoe stores, and any child could have "fun" by irradiating his feet!

You could recommend the famous biography of Marie Curie (see Student Activities) to interested students; most libraries have it. Often, the famous movie based on this book is shown on the "early" or "late" show on television. If there are girls in your science class, they might be interested in knowing that, despite her unique and international fame, the French Academy of Sciences refused to elect her (she missed by one vote)—an interesting comment on the attitude toward women as scientists at that time. (You might ask your class to find out if that attitude has undergone any change during the last 60 years.)

A pertinent article is: "The Early Years of Radioactivity," by G. E. M. Jauncey, in the American Journal of Physics, v. 14, pp. 226-241, (1946).

Sec. 21.3 The penetrating power of the radiation: α, β and γ rays

If your students inquire further about the meaning of the word "range," when applied to the distance traveled by radioactive emanations, you might explain that the less penetrating ones—the particles that are charged—give up their energy gradually as they go along; for example, an alpha particle in air loses about 35 eV for each ion-pair formed, until all its KE is gone; it then captures 2 electrons to become a helium atom. (You might ask your class how many ion-pairs will be formed in air by a 6 MeV alpha particle.) In the same way, the energy of a beta particle is absorbed; however, beta particles have a much wider range of energies than do alpha particles or gamma rays.

Gamma rays, on the other hand, do not ionize air molecules casually as they go along and so do not lose their energy gradually. A gamma ray photon is removed from the beam in a single event—by photoelectron absorption, electron scattering or pair-production.

Sec. 21.4 The identity of α rays: Rutherford's "mousetrap"

It is worth mentioning to your students that the separation of α, β and γ rays illustrated by Fig. 21.1 is, of necessity, greatly exaggerated. (Students doing SG 21.3 will discover that if α and β particles enter a given magnetic field with the same speed, the ratio of their radii of curvature would be 7350:1.) Note that at the bottom of p. 16 it is stated that "The magnitude of the deflections suggests that α particles have a much larger momentum than the β particles." The other possibility to note is that α particles are deflected much less than β particles because they have a much smaller charge. Independent measures of the charge indicated that such was not the case. Students will realize that the greater momentum of the alpha particle could be due to either a greater mass or to a greater speed. The greater momentum was found to be primarily due to greater mass.

Sec. 21.5 The charge and mass of α, β and γ rays

Students will be much aided in their understanding of Rutherford's ingenious "mousetrap" by a brief teacher-led discussion based on transparency T-41.

Sec. 21.6 Radioactive transformation

Though it is correctly pointed out in this section that the establishment of alpha and beta rays as particles coming out of atoms—thus breaking down the earlier idea that atoms were "uncuttable"—you might want to point out that the discovery of cathode rays was also a step in this direction. When Thomson measured e/m for the electron, his empirical work provided the basis for an atom model made of two separate parts. However, you might then ask:

"What is the difference between the electrons of cathode rays and the electrons which are beta rays, in terms of their places in the model of an atom?"

The discovery that radium released heat as part of its radioactivity has had technological consequences. You can refer your students to the photo of the SNAP generator on page 3 of the text, to see how the heat energy resulting from a nuclear event can be transformed to do useful work. You can acquire additional information about SNAP in two publications: Power from Radioisotopes, and Direct Conversion of Energy, by writing to

U. S. Atomic Energy Commission
P. O. Box 62
Oak Ridge, Tennessee 37830.

It ought to be emphasized that the proposal of Rutherford and Soddy that there was a transmutation of elements in the radioactive series was a very bold step, and that their idea was an exciting breakthrough. If the loss of an alpha or beta particle from an atom meant that the result was a different atom, that difference had to lie in a change in the nucleus. Recall the nuclear atom model proposed by Rutherford—from where else could an alpha particle emerge?

Sec. 21.7 Radioactive decay series

The uranium-radium series given in Table 21.1 can be most effectively discussed by referral to T42A. (The term half-life is not defined until the next section; it would be useful to briefly mention its meaning in class and to point out the tremendous range of half-lives listed in Table 21.1.) Discourage students from attempting to learn in detail the decay sequence described on p. 22. It is important to understand the kinds of transformation that take place, but specific examples are for illustrative purposes only.

Sec. 21.8 Decay rate and half-life

The radioactivity decay curve framing p. 24 is a natural focus for class discussion of this section. If students understood what is meant by half-life, they will have little difficulty understanding the shape of the decay curve. They might have trouble though if they don't realize that the units of time on the horizontal axis are "half-lives", i.e., that T represents the half-life of a radioactive substance. It is important to emphasize that knowing that 50% of a sample will decay during its half-life does not imply that we have any way of predicting which atoms of the sample will decay during any given half-life. Of course if the sample size is extremely small, large fluctuations from the predicted decay are likely.

Note that the mathematics of the decay has been set aside on a gray page, p. 26, and will be appropriate reading only for those students who are particularly mathematically inclined.

Sec. 22.1 The Concept of Isotopes

It might motivate your students to realize that with this chapter they are going to begin understanding a physical phenomenon that for hundreds of years was the dream of many men. Ancient, medieval, and renaissance alchemists spent their lives hopelessly searching for the "philosopher's stone," the unique substance that would enable one to change one metal into another (preferably iron, lead, or mercury into silver or gold). Radioactivity and the concept of the nuclear atom, in this sense, are the "philosopher's stone" of modern physical science, for they provide the key to understanding how the atoms of one chemical element can be transmuted into the atoms of another. Perhaps one or two interested students would like to look into the history of alchemy. A fascinating book on this subject is *Through Alchemy to Chemistry*, by John Read, Harper Torchbook #561. Another good source is *The Historical Background of Chemistry*, by Henry M. Leicester, J. Wiley Science Editions, 1965, a paperback.

Sec. 22.2 Transformation Rules

The term "displacement rules" was considered to be misleading and was not used. "Transformation rules" is a far more appropriate term because it is descriptive of the two processes involved.

One question you might ask (if your students don't) is: "Why do the radioactive series elements only lose mass by emitting an alpha particle?" For example, in the gradual change from U^{238} to Pb^{206}, the nucleus loses 32 atomic mass units (and 10 units of charge). Why isn't a nuclear fragment of this size thrown out all at once, instead of a gradual loss of mass and charge by alpha and beta particle emission?

Ask your students to calculate the ratio of mass to charge (A/Z) for such a fragment (3.2), and then ask them to search through the periodic table, or better still, a table of the nuclides if you have one, to see if such a nucleus exists (they must keep testing the ratio A/Z). They will not find such a nucleus in existence. Ask them to consider the possible emission of other particles, like ${}_1H^2$ or ${}_3Li^6$ instead of alpha particles. Would these provide the required change of mass and charge?

Your students should come to the conclusion that since alpha particles are the only significant massive particles emitted by nuclei in the radioactive series, such a particle must exist in the nucleus as an entity.

As a final check, point out that the earth's crust is made up mostly of such stable nuclei as ${}_6C^{12}$, ${}_8O^{16}$, and ${}_{14}Si^{28}$. Can these nuclei each be divided into a whole number of alpha particles?

Sec. 22.3 Direct Evidence for Isotopes of Lead

This section provide a good opportunity to emphasize what it is about the isotopes of an element that enables us to say that they are in fact varieties of the same element. What is it about the four isotopes of lead that makes them chemically identical? Of course it is the atomic number 82 that they have in common. (The atomic number determines the electron configuration of the atom and hence determines all the chemical properties and most of the physical properties.)

That 3 of the 4 naturally occurring isotopes are end products of 3 different decay series is very fortunate—by analyzing rock samples we can determine both the initial composition and age from the relative abundance of the lead isotopes in the rocks.

Sec. 22.4 Positive Rays

The term "canal rays" is often used to refer to positive rays; however, because it is a misleading term it was not used in the text.

Encourage students to study the captions and diagram of the mass spectrograph on p. 37. Students will likely be pleased that their knowledge of a few simple principles enables them to understand the operation of this ingenious device.

Sec. 22.5 Separating Isotopes

Whereas the preceding section dealt with the *theory* of the mass spectrographic determination of the mass of ions and the separation of isotopes, this section recounts Thomson's *experiment* with the mass spectrograph in which he discovered that neon has 2 isotopes.

To understand the work of Aston in separating isotopes by gaseous diffusion, students probably need to be reminded that the average kinetic energies of different species of molecules in a mixture of gases is the same if the temperature of the mixture is uniform. Thus, the lighter ones must, on the average, move faster and hence will diffuse through a porous wall more quickly.

Sec. 22.6 A useful notation for nuclides and nuclear reactions

Although the latest convention for symbolizing nuclides is to write both the subscript Z and superscript A to the left of the element symbol, this convention was not followed in the text because of printing considerations: to separate the superscript and subscript adequately puts them too close to the lines of type above and below.

The proton and neutron do not come into the story-line until the next chapter, but the chart on p. 43 has its axis labeled $A-Z$ vs. Z, and Number of Neutrons vs. Number of Protons. This was done to make the chart more useful to refer back to when reading the next chapter. Note that the first open square (at $A - Z = 1$, $Z = 0$) represents a free neutron.

Point out to students that the large arrow in the diagram on p. 41 is a "process" arrow; that is, it represents a process by which, in this case, U^{238} gives off an alpha particle and becomes Th^{234}. The large arrow does not represent a velocity. (The small arrows shown represent the relative velocities of the reaction products.)

Sec. 22.7 The Stable Isotopes of the Elements and their Relative Abundances

It is interesting to note that if an element with an odd atomic number has two isotopes, the atomic masses of the isotopes will also be odd numbers. For example, the atomic number of chlorine is 17 and it has two isotopes, Cl^{35} and Cl^{37}. The isotopes are stable.

But, for heavy elements, if the element has an odd Z but an even mass number A, that isotope is radioactive! For example, potassium has an atomic number of 19 and has an isotope K^{40} that is radioactive.

If you bring the above generalizations to the attention of the students, stimulating questions might arise as to the reason for these regularities in behavior: i.e. what is it about the nucleus that allows the "oddness" or "evenness" of its composition to determine its stability? You might drop a hint here about the shell model of the nucleus, a model which they will read about in Sec. 24.12.

A point relating to stability that should eventually be brought to the attention of students is the way the plot of the nuclides on p. 43 curves up (away from an imaginary 45° line that would represent equal numbers of protons and neutrons in nuclei.) This up-curving implies that the masses of nuclei go up faster than their charges. At higher Z numbers, the greater positive charge of the nucleus is in effect "diluted" by uncharged matter (neutrons) in such a way that the nucleus is not forced apart by electrostatic repulsion. (This coulomb repulsion is very large due to the extremely small distance between protons in the nucleus.) The effect of the greater proportion of uncharged matter is to give rise to very strong short-range attractive forces which hold the neucleus together.

Another interesting point arises from the chart on p. 43. If you imagine a best-fit "stability line" drawn through the black squares, the unstable nuclides above that line have excessive negative charge (too few protons) for stability and hence undergo β-decay to become stable; whereas those unstable nuclides below the stability line have excessive positive charge (too few neutrons) for stability and hence undergo $\beta+$ decay. In other words, the heavier isotopes of a given element emit electrons, the lighter isotopes of the element emit positrons.

In other words, the heavier isotopes of a given element emit electrons, the lighter isotopes of the element emit positrons. (In addition to positron emission as a way of reducing positive charge, there are other processes such as electron capture and alpha decay which accomplish the same result.)

Sec. 22.8 Atomic Masses

This brief section presents Aston's whole-number rule, which suggests so strongly that nuclei consists of different numbers of identical pieces each of which has a mass of 1 amu.

Sec. 23.1 The Problem of the Composition and Structure of the Atomic Nucleus

At the beginning of this chapter, it might be helpful if the students were asked to summarize the information they would have had at their disposal at this point in history (about 1925) relative to the structure of the nucleus. This might be tabulated on the board. Items such as Rutherford scattering, half-life phenomena, particle energies, knowledge about the electron, isotopic mass variation, etc. might be included. Students should be asked what each piece of evidence might imply about nuclear structure. They should be reminded that the neutron had not been discovered at this time, and also that Heisenberg had not formulated the Uncertainty Principle until the thirties.

A second provoking question to think about throughout the chapter is: what is charge? There is presently no simple answer to this question, and it gives one practice in spinning out hypotheses. An interested student might be asked to look into the present state of inquiry into the nature of charge.

Sec. 23.2 The Proton-Electron Hypothesis of Nuclear Structure

It might not be entirely wrong to say that the whole point of Chapter 23 is the development of answers to the questions: what is the purpose of a model? On what criteria do models succeed or fail? How real is a model? How much do models allow the scientist to understand or explain nature (that is: what are the limitations of models)?

Hopefully, these are the kinds of questions that have been coming up in class during the entire course. The aware student ought to realize that, as the investigation of natural phenomena has passed from the macroscopic world to the microscopic one, the models have become increasingly complex. This makes for an interesting contrast: as we proceed from the behavior of large and complex masses of matter to that of simpler masses, the models go from simpler to more complex.

The proton-electron theory of the nucleus is an interesting example of how a model inevitably depends upon the empirical evidence available at the time. Thus, the proton-electron model works very well, if all you know is that certain heavy nuclei are emitting either alpha or beta particles.

Note that at the end of this section, there is no reason given for the failure of the proton-electron model. Yet, some perceptive student may want to know upon what criteria the model failed. The fact is that the criteria are rather sophisticated. One was the discovery that the nucleus had an angular momentum, called spin. This property could be measured by spectroscopic analysis (very high resolution of hyperfine structure). The result of such analysis is an ability to measure a quantity called the magnetic moment of the proton and electron. It turns out that the magnetic moment of the electron is much larger than the magnetic moments of different nuclei. So, one must ask the question, if there are electrons in the nucleus, why isn't the magnetic moment of the whole nucleus greater than that of the electron?

Sec. 23.3 The Discovery of Artificial Transmutation

There is one question related to the Rutherford observation of artificial transmutation that you might use to stimulate some class discussion: why are the chances of a collision between an alpha particle and the nitrogen nucleus so small (1 for every 10^6 alpha particles passing through the nitrogen gas)?

In terms of the kinetic theory (Unit 3), it seems reasonable that the probability of capture should be much greater.

However, remind your students that kinetic theory does not take into account (1) the extreme smallness of nuclear diameters, or (2) the effect of the electrical fields of the nuclei.

The nitrogen atom has a radius of about 10^{-10}m; however, the nucleus is far smaller, with a radius of about 3.6×10^{-15}m. Imagine a target with a diameter of 300 meters, whose bullseye is only 1 centimeter across! To make things worse, imagine standing a few thousand meters away and shooting at this target blindfolded. What are the chances of hitting the bulls-eye? Suppose all the targets were moving around randomly in space at the same time, what would happen to the probability?

As for the effect of the electric field, the N nucleus has a charge of + 14 elementary charge units, while the alpha particle has +2. Ask your students to calculate, by Coulomb's Law, the repelling force between two such charged particles at a distance equal to the sum of the radii of both particles (the radius of the alpha particle is about 2.4×10^{-15}m). They should be surprised at the result. In fact, they have a right to ask, how is it that an alpha particle ever manages to get inside a nitrogen nucleus? (The answer, of course, is outside the realm of classical physics - only a quantum mechanical analysis can offer an explanation.)

The nitrogen atom has a radius of about 10^{-10}m; however, the nucleus is far smaller, with a radius of about 3.6×10^{-15}. Imagine a target with a diameter of 300 meters, whose bulls-eye is only 1 centimeter across! To make things worse, imagine standing a few thousand meters away and shooting at this target blindfolded. What are the chances of hitting the bulls-eye? Suppose all the targets were moving around randomly in space at the same time, what would happen to the probability?

You can relate Wilson's invention to the Millikan Oil Drop Experiment (Unit 5) by pointing out that Wilson first used his cloud chamber to calculate the charge on the electron. He created the water cloud between two parallel metal plates. First, he observed the gravitational fall of the top surface of the cloud; then he created a uniform electric field between the plates and observed the fall under the influence of both gravitational and electric fields. By comparing the two rates of fall, Wilson calculated a charge of 1.0×10^{-19} coul, about 2/3 of the accepted value today. Ask your students what kind of error could be caused by using a water cloud (evaporation), and why the technique of using single droplets of oil was a better one.

Fifteen years later, Wilson realized that his cloud chamber could be used to observe the tracks of particles from radioactive disintegration. For this work (together with Arthur Compton), he received the Nobel Prize.

Sec. 23.4 The Discovery of the Neutron

This section explains the evidence for the neutron in a fairly clear and detailed fashion, and your students should be able to follow the arguments without much difficulty. Remind them that in this chapter, they are seeing the application of Newton's idea of the universality of the laws of nature. The principles of conservation of momentum and energy came from observations in the macroscopic world; but here they are being applied to the motion of tiny, invisible particles moving with high speeds. Nevertheless, the predictions which are made on the basis of the validity of these conservation principles do check out correctly. (Don't forget the article "Conservation Law" by Kenneth Ford in the Unit 6 Reader.)

Sec. 23.5 The Proton-Neutron Theory of the Composition of Atomic Nuclei

This brief section provides an excellent example of how models change in physics. In the long run, the validity of the model depends only upon how nature behaves. Scientists must accommodate the model to the behavior - not the other way around. You might ask your students to contrast this model change with the attempts to change the solar system model in early astronomy.

If your students are curious, the empirical evidence for the existence of neutrinos was discovered by Reines and Cowan at Los Alamos in a famous nuclear pile experiment. They made a very large neutron counter and placed it near one of the atomic piles at the Savannah River Project. The reaction they were looking for was this proposed one:

proton + neutrino = neutron + positron.

Since the heavy pile shielding kept all other particles except neutrinos from coming through, the appearance of neutrons and positrons in the counter showed that the above predicted reaction was indeed taking place.

Sec. 23.6 The Neutrino

If your students want more information about the neutrino, there was an excellent article in the January 1956 Scientific American by Philip Morrison, "The Neutrino." But first, they should read Chadwick's own notes about the search for the neutron in the Unit 6 Reader.

It might interest your students to know that though Pauli suggested the existence of another particle, the name "neutrino" was coined by Enrico Fermi (it means "little neutral one" in Italian).

For your better students, who might want to know just how the principle of conservation of energy is violated without emission of the neutrino, there is a lively explanation of the neutrino on pp. 134-135 of the paperback book, The Atom and Its Nucleus, by George Gamow (Spectrum Books).

If there is no reading available for your students, point out that a free neutron tends to disintegrate fairly quickly into a proton and a beta particle. However, if we write the nuclear equation as:

$$ {}_0n^1 \rightarrow {}_1p^1 + {}_{-1}e^0 $$

the masses on each side of the equation do not balance. The rest mass of the neutron turns out to be 0.00084 amu larger than the combined rest masses of proton and electron. This rest mass difference represents an energy of 0.78 MeV, which should be the energy of the emerging electrons; however, very few electrons emerge with as much energy as this. So, Pauli suggested the existence of another energetic particle to make up the difference in energy.

How is the conservation of momentum principle violated by the nuclear equation above? If the neutron does break up into only a proton and electron, the two particles should recoil from each other at 180° - that is, they should fly diametrically apart,relative to their center of mass. But observation of the tracks showed that they did not do what the law of conservation of momentum required. The angle of separation suggests that another particle must be part of the interaction.

In the case of beta emission, the missing particle is an antineutrino. (The neutrino and antineutrino are similar particles; the former is associated with positron emission; the latter, with electron emission.)

Tell your students to conceptualize the neutrino as a kind of photon - that is, with zero rest mass and with a velocity = c. But the neutrino behaves quite differently from a light photon; for example, it does not cause a photoelectric effect. In fact, the neutrino rarely interacts with other particles; this is why it has such tremendous penetrating power. Many neutrinos probably pass through the entire earth without interacting with any particles! (The chances of a neutrino interacting with the atoms of your body are only about 1 in 10^{13}.)

Neutrinos are produced in the upper atmosphere by cosmic ray bombardment. They also come from many stars, and some astronomers think that as white dwarfs degenerate into even more incredibly dense stars—black dwarfs and neutron stars—vast numbers of neutrinos are emitted.

Sec. 23.7 The Need for Particle Accelerators

It is interesting to point out the remarkable contrast between the size of the particles that are accelerated and the size of accelerating machines (shown on pp. 68, 69). Similarly, the scale of detection devices such as the Brookhaven bubble chamber assembly shown on p. 70 is worthy of mention. Another thing to contrast with the size of that immense bubble chamber assembly is Glaser's tiny bubble chamber, also shown on p. 70.

Students who might be particularly interested in elementary particles should be encouraged to look through the additional unit "Elementary Particles," (if you have it on hand) and to study it in detail if time permits.

A good paperback book on accelerators for your interested students to read is the Science Study Series (Doubleday Anchor Books), Accelerators: Machines of Nuclear Physics, by Littauer and Wilson.

Sec. 23.8 Nuclear Reactions

The purpose of this section is to emphasize that a change in nuclear charge means a change in place in the periodic table - and this means that transmutation has occurred.

Many examples of nuclear reactions can be found to supplement the few examples in the text. But it might be more interesting and informative for your students to be aware of the Bohr theory of the compound nucleus (proposed in 1936) to explain such reactions. Niels Bohr made two assumptions about the order of events in a nuclear reaction:

(1) the particle that strikes the nucleus is absorbed into the nucleus to form a compound nucleus;

(2) the compound nucleus is unstable and disintegrates by ejecting a particle or gamma photon, with new nucleus formed as product.

Bohr also assumed that the compound nucleus depends upon its own energy state and its angular momentum (and has nothing to do with the way the nucleus is formed). So, in terms of the Bohr theory, the first reaction on p. 72 of the text would look like this:

$$ {}_1H^2 + {}_{80}Hg^{199} \rightarrow [{}_{81}Tl^{201}] \rightarrow {}_{79}Au^{197} + {}_2He^4. $$

Have your students rewrite the nuclear equations in this section and in the following one in terms of the compound nucleus theory.

Bohr assumed that the energy of the entering particle was shared by all the other nucleons in the capturing nucleus - this newly available energy he called the excitation energy. If this energy is large enough, it may provide the means for one nucleon or a combination (like the alpha particle) to escape (this amount needed for escape is called the separation energy—about 8 MeV).

Thus, compound nuclei are formed whenever a nucleus captures a proton, neutron, electron, deutron, alpha particle or even an x-ray photon of high enough energy. In a very short time, the compound nucleus disintegrates to eject a particle and leave a new product nucleus.

Sec. 23.9 Artificially Induced Radioactivity

One of the most interesting cases of induced radioactivity is that of sodium discovered by E.O. Lawrence. He bombarded rock salt with deuterons of 2 million electron-volts energy and obtained radioactive sodium. The reaction can be written

$$_{11}Na^{23} + {}_1H^2 = [{}_{11}Na^{24}] + {}_1H^1$$

followed by

$$[{}_{11}Na^{24}] = {}_{12}Mg^{24} + {}_{-1}e^0$$

with a half life of fifteen hours. The magnesium nucleus, however, is in an excited state and in falling to the normal state emits gamma rays. Hence, radiosodium emits beta and gamma rays identical in nature with those from natural radioactive substances. These gamma rays are more penetrating than those from radium. The advent of induced radioactivity creates new possibilities in biological and chemical research. The active atoms are so easily detected that they can be traced through a process or reaction. They serve as marked or "tagged" atoms which can be located by their effect upon a counter. The time for an in-depth discussion of radiation biology, medicine and agriculture will be in Sec. 24. 13. Today there are far more artificially produced radioactive isotopes than there are natural ones, and there is no essential difference between them.

Sec. 24.1 Conservation of Energy in Nuclear Reactions

The statement that nuclear reactions are far more energetic than chemical reactions can be made more vivid by having your students calculate the number of electron volts of energy released in a typical exothermic reaction.

A well-known reaction is the combining of oxygen and hydrogen to form water. The heat of formation for a gram molecular weight of water is -68.4 kcal (the minus sign means the reaction is exothermic). The steps your students should follow are:

1) change kcal into joules by using the mechanical equivalent of heat:

$$W = JH;$$

2) compute the number of joules of energy released per molecule. Remind your students that there is an Avogadro's number of molecules in a gram molecular weight;

3) change the number of joules/molecule to electron volts.

The students will discover that the total energy released per molecule of water is about 3 eV. And this is considered a fairly energetic chemical reaction!

You can find other values of heats of formation in any chemistry text for other examples of the above.

Sec. 24.2 The Energy of Nuclear Binding

The concept of binding energy (remind your students about the actual definition in terms of "unbinding") brings up the question of nuclear force. When nucleons are held together in a very, very small volume, what kind of force keeps them together? What part is played by the binding energy here?

There is a fine article in the March 1960 Scientific American on the subject about which we still know so little, "The Nuclear Force," by Robert E. Marshak. Gamow also writes about nuclear force, using a very entertaining simile, in The Atom and the Nucleus (Spectrum Books), pages 136-7.

If any student who has heard of the term "mass defect" asks about it with respect to the subject matter of this section, point out that "mass defect" is the same as "binding energy" except that the former is measured in mass units and the latter in energy units.

It may be worthwhile to point out to your students that the conceptualization and measurement of binding energy is responsible for the decision not to use the proton as a standard (with a mass = 1 amu) for all atomic masses. For all atoms with A greater than 12, the mass defect is about 0.0085 amu/nucleon. C^{12} on this scale would have a mass = 11.907 amu, and the mass of U^{238} would be 238.20. Thus, there would be a noticeable discrepancy between mass numbers and the actual numbers of nucleons in nuclei. Actually, any atom more massive than B^{11} could have been chosen as a standard, in order to make the mass numbers nearly equal to the numbers of nucleons; C^{12} was chosen for the reasons given on page 46 of the text.

Sec. 24.3 Stability and Binding Energy

The point to emphasize in this section is the way in which the average binding energy per nucleon varies with the mass number A. Figure 24.1b illustrates that variation; a variation which will be seen in later sections to account for the release of energy in nuclear reactions, and to make possible the large-scale energy release in both nuclear fission and fusion.

Since Fig. 24.1b will be referred back to in later sections, briefly focusing the attention of students on it at this point will be helpful to them in sections to come; but don't take time to go into all its implications—let the implications arise naturally in later sections.

Something which might need stating is that it only makes sense to speak of binding energy per particle when the particle is in fact, bound to other particles. An isolated particle, of course, has no binding energy.

Sec. 24.4 The Mass-Energy Balance in Nuclear Reactions

Here is an excellent opportunity to clarify student understanding of the equivalence of mass and energy. The text describes a nuclear reaction in which a proton is captured by a lithium nucleus, which disintegrates into two alpha particles moving apart at high speed. As shown on p. 85, this disintegration results in a loss of rest mass and a gain in kinetic energy. Students may think—aha! mass has been converted into energy! But this interpretation is valid only if the student is careful to say rest mass and kinetic energy (and/or gamma ray energy). There is no change in total mass or total energy.

Prior to disintegration, the lithium nucleus and proton had a certain total energy, made up of kinetic energy and rest energy—the energy equivalent of their rest mass. After disintegration the total energy is the same as before, but now consists of more kinetic energy and less rest energy!

As total energy is conserved, so is total mass. Suppose measurements of the mass of the alpha particles were made as they separated at high speeds after their formation.* The kinetic energy of the alphas contributes to their relativistic mass, and the total mass so measured would be identical to the total mass of the proton and lithium nucleus prior to the reaction!

However, if we stop them and again measure their mass, we will be measuring their total rest mass, which we will find to be smaller than before (by an amount we call the mass defect of the reaction). Note that mass and energy are still conserved, because the kinetic energy and accompanying mass increase pass by collision and ionization from molecule to molecule of the air through which the alphas travel, ending distributed as thermal motion of the air molecules.

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*The mass measurement at high speed could be made by measuring the initial curvatures of the alpha particle tracks in a cloud chamber in a magnetic field.

Sec. 24.5 Nuclear Fission: Discovery

This section begins the part of the course that should be very exciting for most students; they all know about A-bombs and H-bombs by now. What is important, then, is that they understand 1) exactly what fission is, 2) how it takes place, and 3) what the consequences are. One might add that the students ought to understand how the phenomenon of fission affects nuclear theory; that is, the making of nuclear models.

You might also underline the effect of accident (of a kind) in the case of the Fermi attempts to create transuranium elements. The discovery of reaction products that shouldn't have been there—as Ba^{139} and La^{140}—turned the direction of research toward what resulted in the discovery of fission by Hahn and Strassmann, and in its explanation by Lise Meitner and O. R. Frisch.

It may interest your students to know that Lise Meitner shared the Atomic Energy Commission Enrico Fermi Award in 1966 with Hahn and Strassmann and was the first woman to receive this award.

Sec. 24.6 Nuclear Fission: Controlling Chain Reactions

The text discusses some of the conditions for neutron capture in terms of neutron energy. That is, "slow" or "fast" neutrons are mentioned. This whole subject area is rather complex and the text treatment should be sufficient; however, there is no reason why interested students should not be encouraged to find out more on their own if they so desire.

Some good references for student reading are: The Neutron Story, by Donald Hughes (an Anchor Book paperback); in the August 1965 Scientific American, the article, "Nuclear Fission," by R. B. Leachman; and in the January 1964 American Journal of Physics (vol. 32, no. 1), two articles on the history of fission: "A Study of the Discovery of Fission," by Esther Sparberg, and "Discovery of Nuclear Fission," by Hans Graetzer.

Additional information for the teacher may be found in Contemporary Physics (a Harbinger Book paperback), by David Park, Chapters 6 and 7.

Sec. 24.7 Nuclear Fission: Large Scale Energy Release and Some of Its Consequences

One of the questions you might bring up in class is: if we assume that at the time of the formation of the earth there was as much U^{235} created as U^{238}, how can the present-day ratios of 99.28% U^{238} to 0.72% U^{235} be explained? (Hint: assume the earth is about 5.6 billion years old. The half-life of U^{238} = 4.5×10^9 years; that of U^{235} = 7×10^8 years.)

A quick, but interesting, approximation of the magnitude of nuclear energies can be worked out quite easily in class. This fission of one U^{235} nucleus liberates about 200 MeV of energy. Have your students change this quantity into joules. Suppose you had an Avogadro's number of U^{235} nuclei. How much energy would be liberated? Five times this amount is about 1 kilogram of U^{235}. When they have calculated the equivalent of this amount of energy liberated by the fission of 1 kg, point out that this is more than is liberated by exploding 20,000 tons of T. N. T. The difference between an exploding bomb and a nuclear reactor, of course, is simply the time taken to release the total energy.

Your students would probably enjoy writing to the Atomic Energy Commission in Washington, or to private corporations like Westinghouse and General Electric, for more information about the peaceful uses of atomic power. Most of these agencies have education and information sections for the dissemination of such information free of charge. Local Civil Defense agencies will certainly have information about radioactive fallout. Here is a good opportunity to relate what is being learned in the classroom to the realities of world politics and economics.

A couple of useful reference articles are: "Breeder Reactors," by Alvin Weinberg in the January 1960 Scientific American, and "The Detection of Underground Explosions," by Sir Edward Bullard, in the July 1966 Scientific American.

Sec. 24.8 Nuclear Fusion

Though this section describes to some extent the problems inherent in controlling a fusion reaction, you might pose the questions a little more precisely for your students. For example, if a magnetic field is used to contain the deuterons and tritium nuclei, what will the paths of these particles be in the field? How does this "contain" the charged particles? How could particles "escape," and what would happen if they did?

In this way, you can relate the technology of thermonuclear reactions to fundamental principles already studied in previous Units on electricity, magnetism, and kinetic theory.

The intriguing question "how can thermonuclear reactions be taking place in the sun and stars without a special mechanism of confinement? Would be a nice lead-in to Sec. 24.9. Of course the answer lies in the gravitational fields of such massive bodies.

A discussion of thermonuclear energy always brings up the threat of the H-bomb and its promise of total destruction. Here is a good opportunity to "integrate" with the social science course in your school. There are certainly many books and articles in print on this subject, and discussions of the problem are still continuing on an international scale. A popular publication on the subject is Brighter Than a Thousand Suns, by Robert Jungk, Grove Paperback, Black Cat Series, 1962. Journals like The Bulletin of Atomic Scientists and Daedalus have many articles on the subject. Try to find time for an informal, exciting kind of seminar class on the question of atoms for war or peace.

A pertinent article in the Unit 6 Reader for your students might be: "Calling All Stars," by Szilard.

Sec. 24.9 Fusion Reactions in Stars

The text discussion applies only to "normal," or "main-sequence" stars, of which our sun is one. Special types of stars like white dwarfs, red giants, variables, and supernovae are more complicated and less well understood. Hydrogen is by far the most abundant element in those parts of the universe which we can explore, thus a very large fraction of all the nuclei present will be protons. For interested students, the two nuclear reactions which are thought to occur, are as follows (assign SG 24.15 before discussing)

(1) Carbon-nitrogen cycle

$$C^{12} + H^{1} \rightarrow N^{13} + \gamma$$
$$N^{13} \rightarrow C^{13} + e^{+} + \text{neutrino}$$
$$C^{13} + H^{1} \rightarrow N^{14} + \gamma$$
$$N^{14} + H^{1} \rightarrow O^{15} + \gamma$$
$$O^{15} \rightarrow N^{15} + e^{+} + \text{neutrino}$$
$$N^{15} + H^{1} \rightarrow C^{12} + He^{4}$$

(2) Proton-proton cycle

$$H^{1} + H^{1} \rightarrow H^{2} + e^{+} + \text{neutrino}$$
$$H^{2} + H^{1} \rightarrow He^{3} + \gamma$$
$$He^{3} + He^{3} \rightarrow He^{4} + 2H^{1}$$

Note that for the third reaction to occur, the second reaction must occur twice.

The net effect of both reactions is to form a strongly bound alpha particle from four protons. The carbon cycle is more appropriate to stars which are more luminous than our sun and whose central temperatures are higher. The proton-proton cycle is more important to stars whose central temperatures and luminosities are lower than that of our sun. Both reactions take place in the sun but the proton-proton cycle predominates.

Sec. 24.10 The Strength of Nuclear Forces

The nuclear force is the third type of force your students will have studied; the other two being gravitational and coulomb, or electrostatic, forces. (The magnetic force is not similarly classed because it results from the relative motion of charged particles.)

In the case of nuclear force, however, there seems to be need for a third description that does not seem to have the same kind of logical basis as the first two. How can the tremendous repelling coulomb force between protons (that certainly must overcome any gravitational force) be rendered inoperative? What kind of cohesive power works here? It ought to be evident to your students that anything said about "nuclear force" must indeed be quite speculative.

There is a fairly easy way to demonstrate the techniques of speculation in nuclear theory by developing the argument for the particle called the meson.

You begin with the rather weird assumption that within the space of the nucleus one nucleon might eject a very small particle that would be absorbed by a neighboring nucleon. The new particle would have an amount of energy which can be designated by Einstein's equation: mc^2, where m is the mass of the particle. This new particle, then, could move through the range of "nuclear force"—that is, across a very small distance inside the nucleus. Measurements show that this range is about 1.5×10^{-15} meters.

If we call this distance $\underline{s}$, then the time it takes the particle to move through s at the speed of light is simply $\underline{s}/c$. Now remind your students about the Heisenberg Uncertainty Principle (Unit 5, Sec. 20.5), and indicate that at such a short distance and at so great a speed, this principle must come into play. Then, the energy multiplied by the time interval must be of the order of Planck's constant; that is:

$$\Delta mc^2 \Delta t \approx h/2\pi .$$

Ask your students to compare the units of $\Delta mc^2 \Delta t$ with those of $\Delta p \Delta x$ (the more familiar statement of the principle); they will find that the units are exactly the same. Now, since Δt is the same as $\underline{s}/c$, we can write:

$$\Delta mc^2 \underline{s}/c \approx h/2\pi ,$$

or

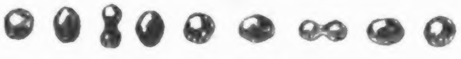
$$m\underline{s} \approx h/2\pi c.$$

Now, your students can fill in the values for h (6.62×10^{-34}), π (3.14), and c (3×10^8). Have them calculate the value of $m\underline{s}$ in kg-m. If they divide this value by $\underline{s} = 1.5 \times 10^{-15}$ m, they will have found the mass of the theoretical particle (it should come out to about 2×10^{-28} kg). Have them compare this mass with that of the proton and electron.

After this calculation is finished, you can point out to your students that they have just worked out a sequence of logical thought similar to that done by Yukawa in order to predict the existence of mesons. In spite of the illogical nature of the assumptions, the tracks of mesons were first identified in 1938 by Anderson in cloud chamber photos of cosmic ray events. Now, at least four different kinds of mesons have been identified. Emphasize the fantastic nature of making a prediction that turns out to be so exact (Anderson's first measurements showed the new particle to have a mass equal to about 200 electron masses), while the "underpinnings" of the prediction are pretty shaky! And this is the way in which much of the predicting in nuclear theory has been going along.

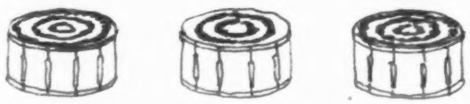
Sec. 24.11 The Liquid-Drop Nuclear Model

The liquid-drop-model, whose ability to account for the variation in nuclear binding energy with mass number and for the process of nuclear fission, depends upon the assumption that interactions occur only between adjacent nucleons. We are all familiar with the characteristic oscillations of a stretched string (Unit 3, page 129), a taut membrane (Unit 3, page 130), etc. Less familiar perhaps are the characteristic oscillations of a liquid drop. It might be well to review briefly just how a liquid drop oscillates with time when disturbed. The students must understand this before they can appreciate the application to fission via the model. A sketch similar to the following might help.



Vibrating liquid drop

Time →



Vibrating drum

Time →

Vibrating string

With this model it is easy to see that once a nucleus is set into oscillation the electrostatic forces of repulsion (positive charges of the protons) between the two halves may drive it into a complete break. This is the fission process.

The question "why doesn't a nucleus separate into three lighter nuclei?" is answered by considering the nucleus to act like a liquid drop, where it seems unlikely that an oscillation would take place in such a mode as to break the drop into three pieces.

The shock that sets a heavy nucleus into oscillation can be delivered by any kind of particle. $_{92}U^{238}$ needs a very large disturbance while $_{92}U^{235}$ can undergo fission by the addition of a neutron with zero kinetic energy. There has been considerable study of photon-induced fission, but for chain reaction, however, the important particle is the neutron.

Sec. 24.12 The Shell Model

There is a good article on the two models (for the teacher) by Aage Bohr (son of Niels) in the November 1957 American Journal of Physics, "On the Structure of Atomic Nuclei" (Vol. 25, No. 8).

Though this subject is not mentioned in the text, your more interested students should, by now, be able to read the articles in the Unit 6 Reader on the problem of a mirror image universe: "The Fall of Parity," by Martin Gardner.

Sec. 24.13 Biological and Medical Applications of Nuclear Physics

The ramifications of this final section are many, and if time permits, you may want to encourage your students to find out more about the use of radioactive tracers. They can write to the Atomic Energy Commission, or to various industries; local doctors or hospitals can probably furnish information on the part played by radioactive isotopes in fighting malignant diseases.

Another interesting feature is the general effect of radiation on animal and plant communities. A good article that concerns itself with this aspect is "The Ecological Effects of Radiation," by George Woodwell, in the June 1963 Scientific American.

Better students who can handle mathematics fairly easily can be asked to investigate the logic of using tracers in agriculture. What is the advantage of using P^{32} (half-life = 14 days) to find out how rapidly a plant takes up phosphate fertilizer?

What the students ought to discover is that only a very tiny amount of phosphate is needed—so little that it could not be detected with the finest analytical balance. Thus, analysis becomes a much simpler task, depending on the counting rate of the detection equipment and the half-life of the tracer atoms.

In the case of P^{32}, it can enter into the plant system as part of a PO_4 radical (phosphate). We can assume that in order to know we are actually counting P^{32} atoms and not random radiation our counter has to count 1000 counts/minute from a 1 gram sample of the plant.

The question is: how much PO_4 has to be taken up by the plant to give this count?

From Sec. 21.8, the students know that the disintegration rate $\lambda = 0.693/\text{half-life}$. If we change the half-life of P^{32} to minutes, λ turns out to be 3.4×10^{-4} per min.

Our required counting rate of 1000/min is simply equal to λ times the number of radioactive atoms needed:

$$\text{number of atoms} = 1000/\lambda = 3 \times 10^6.$$

The students ought to know how many grams of PO_4 represent an Avogadro's number of atoms. Then:

$$\frac{96}{6 \times 10^{23}} = \frac{x}{3 \times 10^6}$$

and $x = 5 \times 10^{-16}$ grams of PO_4 in 1 gram of plant material.

In the case of malignancy, detection of tumors by radioactive atoms became possible only after the less massive, artificial radioactive nuclides were made. Ask your students why the naturally radioactive elements could not be used for such detection. The answer is that such atoms are not taken up naturally by living cells in normal metabolic processes.

An extra exercise, or library research project, might be to ask your students to find out just what the units of radiation are. There is usually much confusion about such units, even though they are used very glibly in popular science articles, usually without proper definition. The units to be checked out are: roentgen, rep (Roentgen Equivalent Physical), and rad. Your students ought to discover that the roentgen only measures numbers of ions produced, and tells you nothing about energy absorbed. Also, the roentgen is based on x rays and gamma rays, and their effect on air.

Transparencies

T40 Separation of α, β, γ rays

Observed deflections of the emanations from a radioactive source are shown in the presence of a magnetic field.

T41 Rutherford's α particle "Mousetrap"

A simplified detail of the apparatus used by Rutherford and Royds in 1909 to show that the α particle is a doubly-ionized helium is presented along with spectra observed during the experiment.

T42 Radioactive Disintegration Series

The four radioactive series: uranium-radium, thorium, actinium, and Neptunium are presented for completion by the teacher and students.

T43 Radioactive Decay Curve

A number of overlays displaying sample data for a radioactive element and its accumulating "daughter" atoms leads to the half-life concept.

T44 Radioactive Displacement Rules

Three types of radioactive decay: α, β^- β^+ are presented in a visualized "before-after" sequence as well as in generalized and specific equation form.

T45 Mass Spectrograph

A schematic diagram of the mass spectrograph with its velocity selector and mass determining sections are shown.

T46 Chart of the Nuclides

A chart of the stable and unstable radioactive isotopes are presented with other pertinent nuclear information.

T47 Nuclear Equations

Visualizations and equations for important nuclear reactions: the first artificial transmutation, the discovery of the neutron, and the mass-energy relation are presented.

T48 Binding Energy Curves

Two plots, one of the total binding energy in MeV vs. the number of nucleons and another of the average binding energy per nucleon vs. number of nucleons, are presented.

Loops

L49 Collisions with an Unknown Object

Elastic collisions between balls of apprpriate relative masses illustrated Chadwick's discovery of the neutron (L).

Non-Project Physics Loops

L6-1 Radioactive Decay (8 mm loop, 4 min, 55 sec).

Assembly of scintillation detector. Samples of Cu 64 and Mn 56 are placed in position. Gamma ray spectra are displayed. Radioactive decay of Cu 64 (half life 12.84 hr) and Mn 56 (half life 2.56 hr).

Distributed by The Ealing Corporation, Cambridge, Mass.

L6-2 Thomson's Positive Ray Parabolas (8 mm loop, color, 3 min, 25 sec, No. 20210).

Mostly animation.

After showing the original apparatus, a beam of positive ions (ne 20) passes through the cathode and strikes the screen. The beam is deflected by electric plates producing vertical line on screen. Magnetic field produces horizontal line. When both fields are applied and the magnetic field is changed, a parabola is produced.

Distributed by Encyclopaedia Britannica Films, Inc., 1150 Wilmette Avenue, Wilmette, Illinois.

L6-3 Aston's Mass Spectrograph (8 mm loop, color, 2 min, 20 sec).

Film opens with shot of Aston's original mass spectrograph, introduces electric plates, passes deflected beam through magnetic field, and also introduces photographic plate.

Distributed by Encyclopaedia Britannica Films, Inc., 1150 Wilmette Avenue, Wilmette, Illinois.

L6-4 Nuclear Reactions—Chain Reaction and Controlled Chain (8 mm loop, color, 2 min, 35 sec, No. 20206).

Animated. Shows various stages of a chain reaction and of a controlled chain reaction around a U235 nucleus cluster.

Distributed by Encyclopaedia Britannica Films, Inc., 1150 Wilmette Avenue, Wilmette, Illinois.

L6-5 Critical Size (Nuclear Reactions: Critical Size (8 mm loop, color, 2 min, 10 sec, No. 20207).

Animated. Demonstrates the importance of critical mass in the creation of a nuclear reaction similar to that taking place in an atomic explosion.

Distributed by Encyclopaedia Britannica Films, Inc., 1150 Wilmette Avenue, Wilmette, Illinois.

16mm Films

F47 Discovery of Radioactivity (16 mm, color.

Distributed by the International Film Bureau, 332 S. Michigan Avenue, Chicago 4, Illinois.

F48 U238 Radioactive Series (16 mm, B&W, min).

The film traces the various stages in the decay of U238 to stable lead. Alpha emission and the statistical nature of the process are emphasized. A brief mention is made of other radioactive series.

Distributed by McGraw-Hill, Text-Film Division, 330 W. 42nd Street, New York, N. Y.

F49 Random Events (16 mm, B&W, 31 min).

This film shows how the over-all effect of a very large number of random (unpredictable) events can be very predictable. Several unusual games can be played to bring out the statistical nature of this probability. The predictable nature of radioactive decay is explained in terms of what is shown.

PSSC Film distributed by Modern Learning Aids.

F50 Long Time Intervals (16 mm, 25 min).

A discussion of the significance of long time intervals with a detailed description of radioactive dating arriving at an estimate for the age of the earth.

Distributed by Modern Learning Aids, 235 Stuart Street, Boston, Mass.

F51 Isotopes (16 mm, B&W or color, 15 min).

The film shows uranium being separated into two isotopes—U238 and U235. It explains how J. J. Thomson first demonstrated the existence of isotopes and how Aston developed the first mass spectrometer. It then shows two methods of separating isotopes and concludes by illustrating the uses of radioisotopes.

F52 The Linear Accelerator (16 mm, B&W, 12 min).

This film introduces the tneory of nuclear transmutations and the production of hard x rays with laboratory accelerated particles. It shows the development and techniques from the original Cockcroft and Walton experiments up to the most recent traveling wave linear accelerator, the design and underlying theory of which are described in detail.

Distributed by McGraw-Hill, Text-Film Division, 330 W. 42nd Street, New York, N. Y.

F53 Positron-Electron Annihilation (16 mm, B&W, 27 min).

Using brief demonstrations, emphasizing conservation of energy, the film "proves" the annihilation, shows the two ½ MeV gamma rays moving in opposite directions.

Distributed by Educational Services, Inc., Film Library, 37 Galen Street, Watertown, Massachusetts.

F54 Principles of Nuclear Fission (16 mm, color, 10 min).

After considering the historic and the modern conceptions of the structure of the atom, the film shows diagrammatically the relation of its basic particles, electrons, protons, and neutrons. It describes in detail how bombarding neutrons causes fission in Uranium 235 atoms and the production of chain reactions. The film then deals with the graphite nuclear reactor, showing methods of controlling action in a nuclear reactor and relating this to the production of electricity.

Distributed by McGraw-Hill, Text-Film Division, 330 W. 42nd Street, New York, N. Y.

Reader

1. RUTHERFORD
Charles P. Snow
1967

C. P. Snow is perhaps best known in this country among scientists for his famous book on the "Two Cultures and the Scientific Revolution," which stresses the separation between the sciences and the humanities, particularly in a British academic environment. He is also a well-known British novelist, with a long series of novels to his credit. The present selection is from a recent collection of short biographies entitled "Variety of Man." Snow had personal contacts with Ernest Rutherford. Snow started as a research worker in the Cavendish laboratory while Rutherford was still director, and his research activities were the basis of an early novel, "The Search." The present selection is not a dull straight biographical selection, but is personal and impressionistic. Most students will find it easy to read.

2. THE NATURE OF THE ALPHA PARTICLE
Ernest Rutherford and T. Royds
1909

Rutherford's experimental techniques, in contrast to those often seen in large laboratories today, were simple enough to be understandable by the beginning student. Rutherford reports on his experiments showing that the alpha particle is a helium nucleus. As he says, this had already been suspected from his earlier work, but the desire was to establish it beyond doubt.

3. SOME PERSONAL NOTES ON THE SEARCH FOR THE NEUTRON
Sir James Chadwick
1962

Chadwick was asked to speak at the Tenth International Congress of History of Science at Cornell University, in 1962, about his discovery of the neutron, work that was done in Rutherford's laboratory. The events described took place some thirty years earlier; memory could be in some instances fallible. However, there is an interesting story here, particularly involving Cavendish's working with and getting assistance from other people.

4. ANTIPROTONS
Owen Chamberlain, Emilio Segre, Clyde E. Wiegand, and Thomas J. Ypsilantis
1956

The student may find this article an interesting contrast to the earlier experimental article in the Reader, Number 2, from Rutherford. Physics has changed in the half-century that elapses between these two! Four people were involved in this work, and generally large groups of people may be collaborating on the same experiment. Students who attempt to read this (not easy) article should be aware, as the first paragraph states, that there was strong theoretical reason for believing in the existence of the anti-proton, even before the experimental work was done.

5. THE TRACKS OF NUCLEAR PARTICLES
Herman Yagoda
1956

The photographic plate fornushes a convenient way of studying the behavior of nuclear particles, because such particles leave tracks in photographic emulsions. The present paper discusses the technique for such observations and shows how different kinds of particles, and different kinds of events, can be studied using the technique.

6. THE SPARK CHAMBER
Gerard K. O'Neill
1962

This article presents another method for "seeing" elementary particles, using the charged "tracks" that they leave in a gas. A high voltage is put across the ends of the chamber, and sparks go along the paths. The author discusses other ways of observing charged particles. This article should be of interest in connection with the "People and Particles" film.

7. THE EVOLUTION OF THE CYCLOTRON
Ernest O. Lawrence
1951

This is Lawrence's Nobel Prize speech, given in 1951. Anyone who reads it will probably read the next "selection" also.

8. THE CYCLOTRON AS SEEN BY...
David C. Judd and Ronald MacKenzie
1967

Commentary seems superfluous!

9. CERN
Jeremy Bernstein
1964

Jeremy Bernstein is a physicist who writes about science for The New Yorker. This article gives a panoramic view of a large contemporary physics research institute. CERN was created for the European situation, with many small nations, pooling finances and talents to make a major research center having the expensive facilities necessary for high energy physics work. This article should be valuable for giving students even at the elementary level, some insight in what it is like to work in a major physics laboratory. Thus in a sense it also complements the "People and Particles" film.

10. MR TOMPKINS TASTES A JAPANESE MEAL
George Gamow
1965

Many students are attracted to the fanciful physics of Gamow's Mr. Tompkins stories. The topic is elementary particles, and the treatment is in the usual light-hearted fashion. The student should know that he is dealing with material at the research frontier, so that if he sees more recent articles he may find different lists of particles than that shown on page 91.

11. MODELS OF THE NUCLEUS
Rudolf E. Peierls
1959

This Scientific American article gives a descriptive view of the theories of the nucleus in use today. None of these theories is entirely successful, but each has ranges of applicability where it does predict more or less correctly.

12. POWER FROM THE STARS
Ralph E. Lapp
1960

One of the major puzzles of physics until recently was the origin of energy of suns. A quick estimate shows that a sun is pouring out an enormous amount of energy. Up until quite recently, there did not seem to be any process that would explain such huge amounts of energy over very long periods. The eventual answer came through an area of physics which seemed to consider very different problems, nuclear physics. This very readable article indicates how thermonuclear power is generated in the sun.

13. SUCCESS
Laura Fermi
1954

The wife of the late Enrico Fermi describes the development of the CP 1 pile at the University of Chicago squash courts; the first critical pile to be constructed, and a major step toward the development of nuclear power. The story is told in a dramatic fashion, fitting the dramatic nature of the events. The same material is also covered in a Project Physics film, "The World of Enrico Fermi."

14. THE NUCLEAR ENERGY REVOLUTION
Alvin M. Weinberg and Gale Young
1966

Until now, power from nuclear reactors has been too expensive for widespread civilian use in this country. But today electricity from such reactors is economically competitive and is projected to become much cheaper.

15. CONSERVATION LAWS
Kenneth W. Ford
1963

This long and detailed discussion will be very valuable for the better student who wants more insight into modern physics than usually offered in the beginning course. Conservation laws, the laws that say that something stays constant while other things are changing, have played an increasingly important role in the development of all physics, and they are one of the central tools of modern elementary particle theory. In addition to the classical conservation laws, such as that for energy and momentum, new conservation laws have been developed for elementary particles. Conservation laws are closely related to another important concept, the invariance of physical laws under mathematical changes.

16. THE FALL OF PARITY
Martin Gardner
1964

One assumption often made in physics early in this century, was that the laws of physics did not have any preference for right-handedness or left-handedness. If one were suddenly to switch the universe around, changing everything that was right-handed in terms of everything that was left-handed, nothing essential would be altered. Like many ideas, this one had consequences which could be tested. In 1956 people tried experiments to verify that this "conservation of parity," particularly in the universe of elementary particles. Rather to everyone's surprise it turned out that parity was not conserved. Martin Gardner, who may be familiar to your students as the author of the mathematical games section of Scientific American, writes in his usual clear and lucid fashion. Other parts of the book from which this is taken may be of interest to students too.

17. CAN TIME GO BACKWARD?
Martin Gardner
1967

Even the beginning student may feel that there is something slightly peculiar about the concept of time, something different from the other kinds of physical variables. He seems to have no control over it. Things just "happen," and we cannot alter the flow of time.

Nevertheless there have always been interesting puzzles connected with time in physics, puzzles which are by no means resolved today. One is that associated with the idea of time as flowing, time as inexorably moving forward. Martin Gardner raises a question which has often been asked, sometimes very profitably, within twentieth century physics. Can we somehow reverse the direction of time, or can we get useful results in physics by assuming that time does go backwards? Perhaps surprisingly, this has been a profitable kind of speculation. This article relates to the two previous articles in the Reader, through questions of invariance and conservation. The telephone conversation between Richard Feynman and John Wheeler is also described by Feynman in his Nobel Prize speech in this reader. Students should see the Project Physics film "Reversibility of Time," in connection with reading this article.

18. A REPORT TO THE SECRETARY OF WAR
James Franck, Donald J. Hughes,
J.I. Nickson, Eugene Rabinowitch,
Glenn T. Seaborg, Joyce C. Stearns,
Leo Szilard
1963

The development of the atomic bomb in the United States was highly stimulated by the known German effort in this direction. (The magnitude of the German effort was considerable. Students would enjoy a recent book, THE GERMAN ATOMIC BOMB, by Irving.) Within the United States, as the likelihood of a bomb became closer and closer, some of the scientists who had worked on the atomic projects became concerned about the social and political consequences of atomic energy. The Metallurgical Laboratory in Chicago, where little active work was then going on compared to such feverish places at the time as Los Alamos, was a center of such thought. The German atomic bomb was obviously no longer a threat, and these physicists worried about what would happen if a bomb were developed. The Franck Report was an attempt to influence the American government's policy with regard to the bomb, and to advise on the future political and social consequences. In lieu of later developments, many things in this report appear almost prophetic.

19. TWENTIETH BIRTHDAY OF THE ATOMIC AGE
Eugene P. Wigner
1962

A distinguished theoretical physicist presents a somewhat different attitude toward the development of atomic energy from that reflected by the authors of the Franck Report, the last selection. The student should view this as a personal statement by a distinguished individual, trying to represent his own feelings in these issues.

20. CALLING ALL STARS
Leo Szilard
1961

Szilard was in the forefront on the physicists who tried to influence the development of atomic energy, both in military and civilian directions, after the war. He used a number of techniques for this, including the science fiction stories in his very interesting book, VOICE OF THE DOLPHINS. This excerpt from that book is a warning concerning the ultimate possible consequences of the use of atomic energy.

21. TASKS FOR A WORLD WITHOUT WAR
    Harrison Brown
    1960

    Brown gives prospects for the future and the urgent work that can be done if the energies of scientists and engineers can be fully devoted to such work in a more politically stable world.

22. ONE SCIENTIST AND HIS VIEW OF SCIENCE
    Leopold Infled
    1941

    This excerpt from Infeld's autobiographical QUEST is an extremely personal statement by a noted Polish theoretical physicist. Students may be surprised, particularly if they have some of the stereotyped images of the scientist, as to the extreme passion reflected in this brief passage, and the concern for social issues at the end of the selection. This is recommended reading for your classes.

23. THE DEVELOPMENT OF THE SPACE-TIME VIEW OF QUANTUM ELECTRODYNAMICS
    Richard P. Feynman
    1965

    This is Feynman's Nobel Prize lecture of 1965. Many sections will certainly be too difficult for the average high school student. Nevertheless, it is felt that the speech has interesting insights into how one kind of physics, fundamental theoretical physics, is conducted. Better students who want insight into twentieth century physics should be encouraged to read the article, with the understanding that they will not be able to follow all the details.

24. PHYSICS AND MATHEMATICS
    Richard P. Feynman
    1965

    This excerpt from Feynman's Messenger Lectures, available on films from B.B.C. and others, discusses a central issue in physics, how physics and mathematics are interrelated.

D59: Mineral Audioradiograph

Autoradiographs played an important role in early discoveries of radioactivity. For example, in 1895, in the set of experiments in which Roentgen discovered x rays, he developed a photographic plate which had been accidentally exposed while lying near an apparatus which emitted x rays. Later, while attempting to expand one part of Roentgen's work, Becquerel discovered natural radioactivity when he developed a photographic plate which had been exposed to the phosphorescent substance, potassium-uranyl sulfate, under conditions in which Becquerel only expected a weak image. (See Section 21.1 in Unit 6 or pages 657-8 in Holton-Roller). Autoradiographs are still used for work with tracers, etc., and can provide some quick and useful evidence of radiation.

This demonstration on the "Becquerel effect" is designed as an introduction to radiation and should be used as the first piece of evidence of spontaneous radiation and its effects. The demonstration might even be done before the first reading in Unit 6 is assigned. The techniques used here are also used later in a tracer experiment on plant growth.

Equipment

Polaroid sheet film, and film roller or camera back for sheet film for development. (Better results are obtained using a thick emulsion x-ray film such as Eastman-No-Screen, but this also requires darkroom supplies for development.) We would encourage those who have developed films to do this experiment by wet-method, i.e., using a darkroom, so that students will see it at least once.

Kit of six samples of materials (three of which are radioactive). It is also desirable to have a watch with a radium flourescent dial (a prewar watch is likely to act as a strong source).

Procedure

The specimen samples should be placed on the film and left for over forty-eight hours. A watch, if it is a strong source, needs less than twelve hours' exposure. A 50-microcurie source of Ti^{204} will produce a noticeable mark in fifteen minutes. After exposure, the film is developed, and the question raised as to the cause of the exposed areas and how it passed through the paper wrapper covering the film.

D60: Naturally Occurring Radioactivity

It will probably come as a surprise to most students that even very "ordinary" things can be radioactive. Radioactive matter does not have to be artificially made, nor is uranium the only naturally occurring radioactive element.

Natural potassium contains three isotopes: K^{39} and K^{41} which are both stable, and K^{40} which decays by β-emission to Ca^{40} (which is stable). The approximate natural abundances of the three isotopes are K^{39}, 93%; K^{40}, .01%; K^{41}, 6.9%. The half-life of K^{40} is 1.3×10^9 years. A straightforward calculation (based on the natural abundance, half-life, Avogadro's number) shows that there should be about 10^6 disintegrations per minute in one kilogram of naturally occurring potassium chloride. Of course, not all the emitted β particles will ever be counted, but the calculation certainly indicates that with a suitable geometry a count significantly above background should be obtained.

The β radiation is at 1.32 MeV and can be counted with the Project Physics GM setup.

Make sure that the KCl is as close to the window of the tube as possible. A count of 40 to 60 per minute (i.e., 2-3 × background) should be obtained; it is not necessary actually to count to appreciate the difference.

Connect the counter system to an amplifier and speaker that will let the whole class hear or see the pulses. Demonstrate the background level before and after the KCl count.

It is a good idea to use "Analytically Pure" KCl, to bring home the point that the radioactivity is not an impurity, but that all naturally occurring potassium contains a small amount of the radioactive isotope.

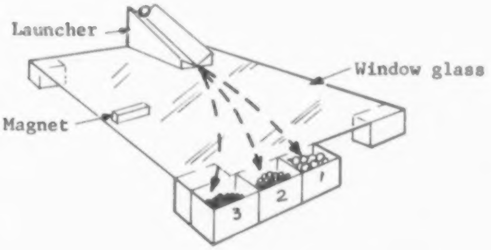
Two points for discussion

1. The material contains less than .01% of radioactive material. (About half this amount because KCl is roughly half K, half Cl, and the Cl is not radioactive.) It has a half-life of about 10^9 years. The count rate is about one disintegration per second. These numbers give us a feeling for the number of atoms present in the sample or alternatively for the size of an atom. In 10^9 years time the rate will be down to about one every two seconds, and, taking the "average" decay rate about one per second, $1 \times 60 \times 60 \times 24 \times 365 \times 10^9$ atoms will have decayed. This number (of the order of 10^{18}) is about half of .01% of the total number of atoms present and close enough to the Geiger tube so that the β particles they emit reach it.

2. Ask students with an interest in chemistry: if potassium salts always contain K^{40}, and K^{40} decays to Ca^{40}, how can any potassium compound ever be obtained free of calcium? And if a calcium free sample were obtained by chemical separation, would it remain calcium free? How quickly would it become contaminated? (Not very—about .0025% Ca^{40} after 10^9 years!)

D61: Mass Spectrograph

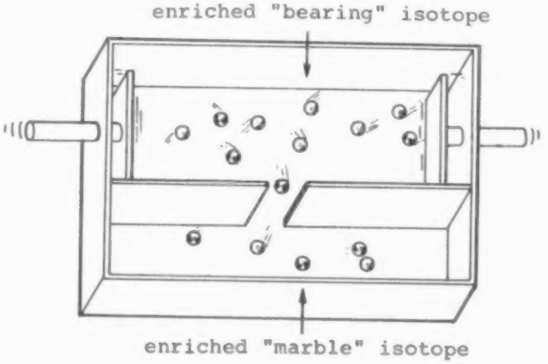
To construct the model of the mass spectrograph mount a piece of window glass horizontally and place a strong magnet under it, close to the glass; for the inclined "launcher," fold several index cards and attach them to the glass with rubber cement. When ball bearings of various sizes are launched from the incline to roll across the glass along a path that passes near the magnet, the larger bearings are deflected less than the smaller ones. If boxes are placed at the edge of the glass, as shown in the figure, each will catch bearings of a different, given size (or range of sizes). Adjustments can be made by changing the position of the magnet. The bearings can be launched in any order; however, if the launching rate is too rapid, the fields induced in the bearings will interfere with the paths of consecutive bearings.



If some students wish to build such a model, its inadequacies should be thoroughly discussed. Does the model have a velocity selector? No, but a single calculation shows that bearing velocities at the bottom of the ramp are constant: $mgh = \frac{1}{2} mv^2$, $v = \sqrt{2gh}$. Is the deflecting force similar to that in the mass spectrograph? No, in that the qvB force in the mass spectrograph exists in discrete multiples of the charge on the particle, and as a function of v; while here it is a function of the ferromagnetic mass of the bearing, and independent of v.

D62: Aston Analogue

An analogue of Aston's porous plug isotope separation might be constructed by interested students as follows: Hand operated pistons at the sides of a box generate fairly random motion of the contained marbles and steel bearings (of the same size). A hole in one of the other sides of the box allows the "molecules" to escape, and should favor the lighter, faster-moving marbles. N.B., this analogue has never been constructed and may not work. If not, discuss why not.



LOOP 49: Collisions with an Unknown Object

It is intended that this film be used to encourage interest in Chadwick's experiment; obtaining the numerical value of the unknown mass is not as important as the experience of finding it by an ingenious indirect method.

In the slow-motion scenes, the collisions have been planned to occur near the left of the frame, so that there can be no attempt to measure the incoming ball's velocity v.

The iron balls used for the film were hardened by heat treatment after holes for the suspension strings were drilled. Evidently the treatment was insufficient; the collisions are not very elastic. As shown in the student notes, the coefficient of restitution e need not be known, but it should be the same for the two events. However, in case 1, e is about 0.44, and in case 2, e is about 0.64. Thus the assumption of constant e is not correct for the actual filmed experiment. The numerical value of m found by the student will therefore be in error. However, this point need not be stressed, since the film's main purpose is to illustrate Chadwick's indirect method of finding the neutron's mass. In Chadwick's neutron experiment, the target nuclei did not store any potential energy, and the collisions were indeed perfectly elastic, with $e = 1$ in each case.

From measured values of V_1 and V_2 and the given values of M_1 and M_2, the unknown mass m turns out to be about 460 grams. For most students this should be the end of the experiment—they have determined an unknown mass by indirect measurements, using a method entirely analogous to Chadwick's historic experiment.

For the teacher's background information, m was actually 449 grams, i.e., within 1 per cent of the mass M_1 of the smaller target ball. Also, the velocity v_1 can be measured from the film (in violation of the spirit of Chadwick's experiment!) If m and v_1 are known, we can find v using Eq. (2), and then we can find v_2 using Eq. (3) (it turns out to be negative). In this way all the velocities become known, and the coefficients of restitution can be found:

$$e_1 = (V_1 - v_1)/v = 0.44$$

$$e_2 = (V_2 - v_2)/v = 0.64$$

It is this difference between the elastic behavior of the balls that accounts for the lack of precise numerical agreement between the computed mass m and the true value (not given in the student notes).

The answers to the questions are:

(1) In our experiment, $M_2/M_1 = 12.2$; in Chadwick's experiment, $M_2/M_1 = 14.0$.

(2) $e = 1.000$ in Chadwick's experiment.

(3) $$v = \frac{(M_2 - M_1)(V_1V_2)}{(1 + e)(M_2V_2 - M_1V_1)}.$$

E44*: Random Events

Many phenomena occur in a completely random way. The rolling of dice and the breakdown of unstable atomic nuclei are two convenient examples for laboratory study.

This group of experiments should heighten students' appreciation for three important ideas:

1. As well as the variation in data introduced by difficulties in the measuring process (e.g., scale interpolation etc., as discussed briefly in Experiment 9*: Newton's Second Law, etc.). the observed quantity itself (e.g., number of radioactive nuclei disintegrating per minute) may vary from observation to observation.

2. Although the outcome of single events of this kind (roll of a die or count of radioactive breakdowns in a minute) is unpredictable, it is quite possible to get useful information about such randomly occurring events provided enough events are observed.

3. This useful information follows from the properties of the regular pattern of distribution that evolves as the number of random events grows large. The larger the number of observations the more precise become the deductions and predictions that can be made.

Divide students into three groups so that each student does only one of the following three experiments.

Equipment

Dice Before class, put a large spot on one side of each of the 20-sided dice with the marking pen provided. Provide a container about the size of a shoe box for shaking the dice. It may be necessary to muffle the sound of shaken dice to prevent interference with the students who are listening to Geiger counter "clicks".

Geiger tube Determine the mean background count rate for your Geiger tube before class. Then choose a time interval for the experiment such that students will observe from 5 to 10 "clicks" per time interval when they are obtaining their data. In order to get a reasonable amount of data in one class period with the tube supplied by Project Physics you may need to increase the count rate by placing a radiation source at such a distance from the tube that 5-10 counts are recorded in about 15 seconds. On the other hand the background rate may already be as high as this in some locations.

Cloud chamber Prepare the cloud chamber by placing the alpha source inside and putting a small barrier nearby (Fig. 1); this can be a 1" x 2" piece of cardboard with a small hole in it, folded to form a V so it will stand on edge. The hole should be to the side of the needle. Relatively few particles emerge parallel to the needle from its end. The size of the hole must be determined by trial; for ease in counting, tracks should appear beyond the hole in the barrier at not more than about one per second.

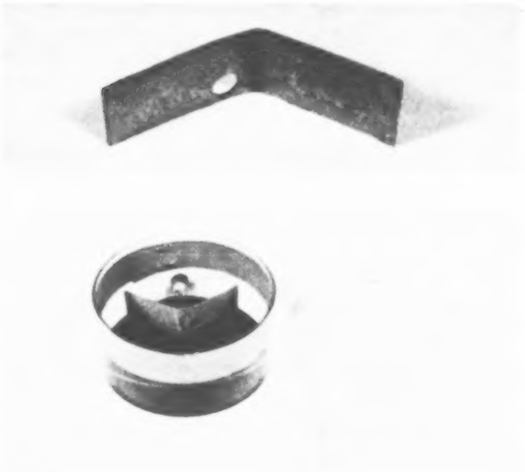


Fig. 1

Moisten the felt or paper ring in the chamber with alcohol and place the chamber on a slab of dry ice. If dry ice is not available, aim the nozzle of a CO_2 fire extinguisher at a pad of cotton or other insulator and discharge the extinguisher at it briefly. The resulting CO_2 "snow" should operate the chamber for several minutes before it must be replenished. Make sure your fire extinguisher does contain CO_2 (and not foam, for instance!) before trying this. To observe, direct a fairly bright beam of light horizontally across the chamber. A flashlight, small spotlight, light source from Millikan apparatus, or slide projector will do.

If the experiment (E45*) on the range of alpha and beta particles is going to be done later you can have students measure the source-to-hole distance and the area of the hole. They will then have all the data they need for the first half of the range experiment.

The counts of alpha particles in the diffusion cloud chamber may be adversely affected by several factors.

1. It is difficult to maintain a constant temperature gradient in the cloud chamber for any length of time. The dry

ice continually disappears and the alcohol evaporates from the blotter and may trickle down the sides of the chamber. The light source tends to warm the chamber. Due to all these slow changes, the conditions for observing tracks probably deteriorate during the experiment.

2. The static electric charge on the plastic container slowly changes, altering the clarity (fuzziness) of the tracks unless you rub the cover occasionally with a clean dry cloth.

3. If a flashlight is used, its intensity slowly decreases, decreasing also the probability of seeing all the tracks in a given region.

Obtaining the data

Assign students to teams according to the number of sets of apparatus you have.

If possible, have the recorder for each team display his data on the blackboard or a large sheet of paper using the kind of table suggested in the student's notes. The entire class can then watch the developing regularity of the patterns of numbers. If the teams work efficiently they can each obtain at least a hundred counts in a single class period.

Table 1

number of tracks observed in one minute (n)	number of times observed (frequency) (f)	total number of events observed (n x f)
0		0
1		0
2		0
3		0
4	1	4
5	11	10
6	1	6
7	~~1111~~	35
8	1111	32
9	~~1111~~ 1111	81
10	~~1111~~ 11	70
11	111	33
12	1111	48
13	1111	52
14	1111	56
15	1	15
16		0
17	1	17
18	11	36
19		0
20	1	20
21		0
22		0
23		0
24		0
25	1	25
	5	540

Mean, $\bar{n}$ = 11

Typical data from the cloud chamber follows in Table 1 and Figure 2.

Analyzing the data

Stress the point that there is no "correct" histogram. But the larger the number of observations the more closely the results approach the pattern predicted by probability theory.

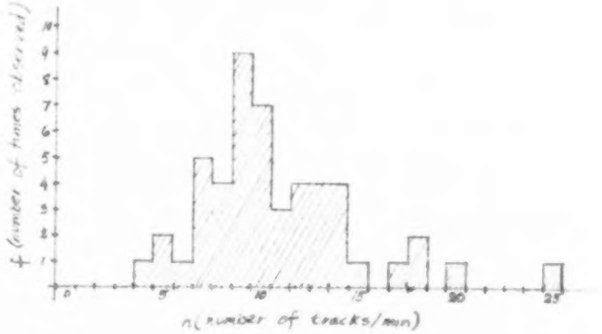


Fig. 2

Notice that the histogram in Fig. 2 is lopsided. This will always occur when the mean value (11 in this case) is small. Moreover, when the mean is as small as this the mean ± √mean range will enclose more nearly three-quarters of all the observations as the number of data grows very large.

The fraction of all observations included in "mean ± √mean" range for various mean values is given in Table 2. (This table refers to the theoretically predicted distribution—see below—not to actual results based on a limited sample.)

Table 2

$\bar{n}$	Fraction within $\bar{n} \pm \sqrt{\bar{n}}$
4	.8166
9	.7600
16	.7413
25	.7295
36	.7217
100	.7080

In Table 2 it can be seen that fraction of observations included in the "mean ± √mean" range decreases towards two-thirds as the mean value grows large.

The fact that the fractions that students report vary from these values should not cause concern since the tabulated fractions are approached only for very large samples. Students doing the present experiment gather so few data, even in several class periods, that the fraction of their results in the range, mean ± √mean, will fluctuate rather sharply above and below the "two-thirds" figure mentioned. And as pointed out in the Student Handbook the range mean ± √mean is difficult to interpret when √mean is not a whole number. So for this experiment the precision implied by Table 2 is quite irrelevant.

Strictly speaking from count = mean ± √mean (with 2/3 probability) it follows that mean = count ± √mean (with 2/3 probability). But if one is trying to estimate the mean this formula is not much help since √mean is obviously unknown. The expression mean = count ± √count given in the Student Handbook is used instead.

Students who are interested in probability theory will want to explore this matter further. Several excellent books on probability are available, including Lady Luck, by Warren Weaver; Facts from Figures, by M.J. Moroney; and Mathematics for the Million, by Lancelot Hogben. These books explain the various kinds of distributions to be expected from observations of random behavior. The distribution that applies to this experiment on random events is called the Poisson distribution. Stated in formal terms, the probability of observing n events per unit time when the mean of a great number of observations is $\bar{n}$ is given by

$$P(n) = \frac{\bar{n}^{n}\, e^{-\bar{n}}}{n!}$$

It has been found by experiment that measurements of radioactive decay fit this distribution very well.

The theoretical distribution for 1000 observations given in the Student Handbook was obtained by setting $\bar{n}$ = 6 and letting n take the values 0, 1, 2....in the above expression.

E45*: Range of Alpha and Beta Particles

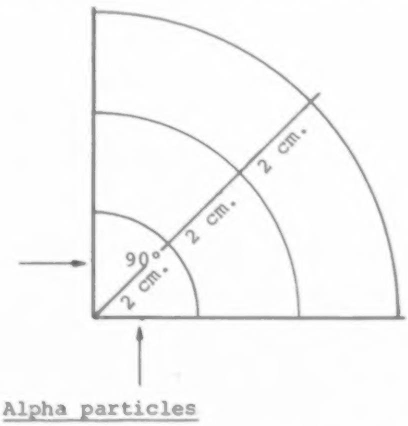
One important idea to emphasize is that different kinds of radiation, though invisible to the eye, have observably different properties and require different instruments for their measurement.

Another idea is the manner in which alpha and beta particles lose their energy. Their loss of energy by the ionization of matter is one of the significant reasons for the effect radiation has on people and is one of their useful properties as tools for studying the structure of atoms.

There is nothing in the following experiment that requires the students to have studied the text on the properties of alpha and beta rays. Hence this may be treated, if desired, as a "discovery" exercise.

If students doing the random events experiment measured the size of the hole through which alpha particles were counted and also its distance from the source, they are almost ready to do the first half of the present experiment as an exercise in calculation. They already have their data except for a measurement of the range of the alpha particles.

In addition to the materials in the equipment list (p. 10) you or the students need to make a distance scale on the bottom of the cloud chamber by scratching the black paint on the underside in the pattern shown below.



Alpha particles

Students may observe alpha tracks of energies as high as 6 MeV, although they should notice that the length of tracks does not vary much. In general, alpha energies of naturally radioactive sources vary from 4 to 8 MeV, but for a particular source, they cluster closely around one principal energy. One source often supplied with cloud chambers is radium DEF which emits alphas of 5.3 MeV.

The following typical calculations involving alpha particles are based on the data tabulated in the preceding experiment on random events. (Teacher Guide: Table 1 and Fig. 2.) It was shown there that the mean count was 11 alpha particles per minute emerging through the small hole.

From the geometry of the cloud chamber arrangement (noted on graph, Fig. 2) we can find the total number of alpha particles (true count) by proportion.

$$\frac{\text{true count}}{11/\text{min}} = \frac{4 \times 3.14 \times 2.5 \times 2.5\ \text{cm}^2}{0.5\ \text{cm}^2}$$

$$\text{true count} = 1727/\text{min}$$

These particles are observed to have a range of about 3.8 cm and hence (from Table 1) an energy of 5.3 MeV each.

The total energy of all 1727 particles/min will therefore be

$$\frac{1727}{\text{min}} \times 5.3\ \text{MeV} = \frac{9150\ \text{MeV}}{\text{min}}$$

Converting this to joules

$$\frac{9150\ \text{MeV}}{\text{min}} \times 1.6 \times 10^{-13}\ \frac{\text{joules}}{\text{MeV}}$$

$$= 1.46 \times 10^{-9}\ \frac{\text{joules}}{\text{min}}$$

or to calories

$$1.46 \times 10^{-9}\ \frac{\text{joules}}{\text{min}} \times \frac{1\ \text{cal}}{4.18\ \text{joules}}$$

$$= 0.349 \times 10^{-9}\ \frac{\text{cal}}{\text{min}}$$

To generate the necessary 100 calories would require

$$\frac{100\ \text{cal}}{0.349 \times 10^{-9}\ \text{cal/min}} = 5.5 \times 10^5\ \text{years}$$

which is why calorimeters are not used as radiation detectors, and why very much "hotter" sources are in nuclear power plants.

As a final note on the alpha-particle experiment it is worth observing that the luminous paint on old (pre-World War II) watch dials (and on some new ones too) emits alpha particles of a wide variety of ranges from the accumulated decay products of the original radium.

Beta particles

The curve of beta particles counted by the G-M tube against the thickness of absorber looks like an approximately exponentially-decreasing one. If all the betas could penetrate the same thickness of absorber, the curve would be flat up to the given thickness, then drop sharply off to the background count. Curves made with different absorbers should have the same form, but with differing half-value thicknesses—that is, the thickness of absorber required to reduce the count rate to just half what it was when no absorbers were between the source and the Geiger tube.

If the curve is plotted on semi-log paper with counting rate along the logarithmic axis, the graph is nearly a straight line for high counting rates and thin absorbers. Then as the absorber thickness increases the rate of decline slows, which means that the straight line curves to become more nearly horizontal. It is as if additional layers of absorber were decreasingly successful in absorbing additional beta particles.

The explanation for this effect is quite interesting. In Unit 4 it was explained that an accelerating electric charge must radiate energy. Beta particles are electric charges and they are being accelerated (negatively) in the absorbing material. The electromagnetic radiation they emit, called "bremsstrahlung," is being detected by the Geiger counter and added to the counts of the beta particles. The thicker the absorber the larger is the fraction of counts due to bremsstrahlung.

E46*: Half-Life I

Exponential growth and decay occur in so many natural processes that it is important for students to study examples in the laboratory. Three kinds of exponential decay are described in this experiment; students may be able to think of other examples to investigate on their own. The results of students' observations are examined graphically, and knowledge of the mathematics of exponents and logarithms is not assumed. Teachers may choose to have students use semi-log paper for their graphs or to plot logarithmic values if this seems appropriate.

Preparing for the experiment

A. Twenty-sided dice (eight-sided dice, optional). As in the experiment on random events (E44*), a shoebox is convenient for shaking the dice. You can save time by having the dice marked before class. The Student Handbook suggests marking two sides of each die. This means that twice as many marked sides show after each shake, and the experiment proceeds more rapidly. One side will already be marked from the previous experiment. Mark a second side in another color (so that experiments requiring a one-in-twenty probability can still be done).

B. Electric circuit. Refer to the circuit diagram.

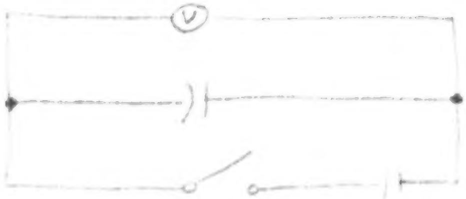


Fig. 1

The capacitor suggested by Project Physics has a capacitance of 6000 μF—a high value of capacitance is necessary to give a reasonably long time constant. Closing the switch* causes the battery to charge the capacitor; when the switch is opened, the capacitor discharges through the voltmeter. The difference in potential V across the capacitor is a function of the time t which has elapsed after the switch is opened, the capacitance C, and the resistance R of the voltmeter:

$$V = V_o e^{-\frac{t}{RC}}$$

where V_o is the initial value of V, at $t = 0$.

The quantity RC is called the time constant of the circuit. When R is in ohms and C in farads, the dimensions of the product are seconds. The quantity $\frac{1}{RC}$ in this expression is analogous to the quantity λ, the radioactive decay constant. The "half-life" of the circuit is

$$T_{\frac{1}{2}} = \frac{.693}{\lambda} = .693\ RC.$$

It will not be necessary to go through this calculation with students. However, the information given here will enable you to select suitable values for R and C. For example, a 2.5V dc meter would typically have a resistance of 10,000 ohms/volt, i.e., a resistance of 25×10^3 ohms. With $C = 6 \times 10^{-3}$ farads, this gives RC = 150 seconds and $T_{\frac{1}{2}} = 104$ seconds. (A simple way to charge the capacitor to 2.5V—or any other desired voltage below 6V—is to use the Project Physics amplifier/power-supply unit. Simply set the dc offset control to the required voltage and connect the capacitor across the output.)

Do not exceed the maximum voltage indicated on the capacitor, and be sure to observe the polarity markings; large capacitors are usually electrolytic and are damaged if their polarity is reversed.

Of course other meters can be used too. A typical multimeter (volt-ohm-milliammeter) has a dc impedance of 20,000 ohms per volt, so that R = 20,000 ohms on the one-volt scale, 200,000 ohms on the ten-volt scale, etc. A vacuum tube voltmeter typically has a resistance of about 10 megohms. This will give a time constant of $T_{\frac{1}{2}} = 0.693\ RC = 0.693 \times 10 \times 10^6 \times 6 \times 10^{-3} = 41 \times 10^3$ secs—too long for an experiment. R must be reduced by adding a resistor (e.g., 10,000 ohms) in parallel with the meter and capacitor.

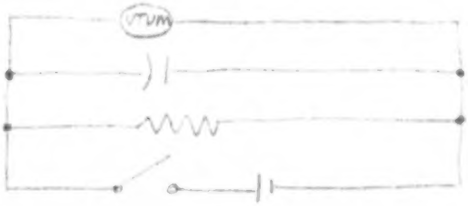


Fig. 2

On the other hand, if you have to use a meter with a low resistance, you will need to put additional resistance in series with the meter. For example, if the meter resistance is 1000 ohms and C = 6000 micro-farads, RC = 6 seconds, which is much too short a time. Putting an additional 9000 ohms in series with the meter makes R = 10,000 ohms and RC = 60 seconds. The voltmeter reading will now be only a fraction (in this instance one tenth) of the total voltage across the capacitor, but it will still vary with time in the same way. To get a nearly full-scale voltmeter reading when the capacitor is charged, the voltage across the capacitor must be ten times the full scale reading of the meter.

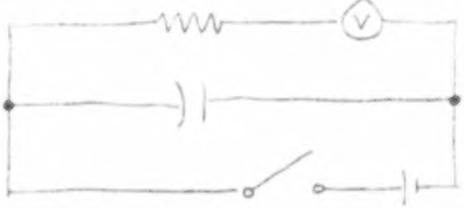


Fig. 3

C. Short-lived radioisotope. This experiment requires quite a bit of advance preparation by the instructor. However, students should find working with a short-lived isotope a rewarding experiment, well worth a little extra effort. The advantages of this particular method are:

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*A switch is not essential; one can make and break contact with a clip lead.

(1) the starting material, thorium nitrate, can be purchased from chemical suppliers at any time and stored indefinitely; (2) the isotope to be used has a half-life of only 3 minutes, so students can observe its decay over several half-lives in one class period; (3) the procedure is relatively safe since the isotope decays quickly to a stable end product.

The experiment is based on the fact that a thorium compound contains not only thorium atoms, which are naturally radioactive with a half-life of over 10^{10} years, but also a series of daughter atoms, as explained in the student text. The isotope used in this experiment, thallium 208, is separated from the mixture by selective adsorption when the dissolved salts are poured over a layer of ammonium phosphomolybdate on filter paper.

The decay of thallium (Tl) may be written

$$_{81}Tl^{208} \xrightarrow{\beta} {}_{82}Pb^{208}$$

The materials to prepare in advance are:

(a) dilute nitric acid. Place in a flask or bottle 25 ml of concentrated nitric acid diluted to 200 ml with distilled or deionized water.

(b) thorium nitrate solution. For each series of counts to be taken, dissolve 6 grams of thorium nitrate in 12 ml of dilute nitric acid. In other words, if you expect to have the experiment performed 5 times in a day, dissolve 30 grams of thorium nitrate in 60 ml of dilute nitric acid. However, after the solution has been poured over the adsorbing material to remove the thallium 208, the decay of other members of the thorium series very quickly replaces the thallium in the filtrate. In theory, you should be able to continue using the same solution indefinitely, simply waiting 10 or 15 minutes between successive filtrations.

(c) ammonium phosphomolybdate. This is supplied as a yellow powder. Place it in a bottle, add distilled water and shake vigorously. The powder is insoluble and will form a slurry.

The experiment

A. Twenty-sided dice. Students are asked to shake the dice and remove those with a marked side on top. Since the dice have two marked sides, the probability that a marked side will appear on top is one in ten: this is analogous to a radioactive decay process with $\lambda = 0.10$ per observation. The half-life is

$$T_{\frac{1}{2}} = \frac{0.693}{\lambda} = \frac{0.693}{0.10} = 6.9 \text{ shakes.}$$

After 7 shakes, the dice should "decay" from 120 to 60; after 7 more shakes, 30, etc.

The Student Handbook suggests alternatively that students shake the tray 5 times, find the average number of spots showing for the 5 shakes and remove that number. This is time-consuming but may be necessary if students are to be convinced that the number "decaying" is proportional to the number shaken.

The reason for plotting two graphs, one showing the number of dice removed per shake and the other the number remaining, is to show that the curves have the same shape. Averaged over many shakes, or—which amounts to the same thing—if the sample is large enough, the number of dice removed per shake is proportional to the number of dice remaining: $\Delta N \propto N$. This is the key idea of exponential decay processes and the fundamental law of radioactive decay.

A more elaborate version of this experiment, which is analogous to a radioactive decay series, is as follows: each time a 20-sided die is removed, replace it with an 8-sided die which has one side marked. (For this experiment the 20-sided dice should have a one-in-twenty probability of decay—ignore the second marked side.) After each shake record the number of each kind of die which has a mark on top. Then remove 20-sided dice with marked side up and replace with 8-sided dice; and replace all marked-side up 8-sided dice with balls (representing stable atoms). Count the number of 20-sided dice, 8-sided dice and balls remaining in the tray after each shake. When the resulting numbers are plotted, the graph will look like the one in the text illustrating the decay of polonium 218

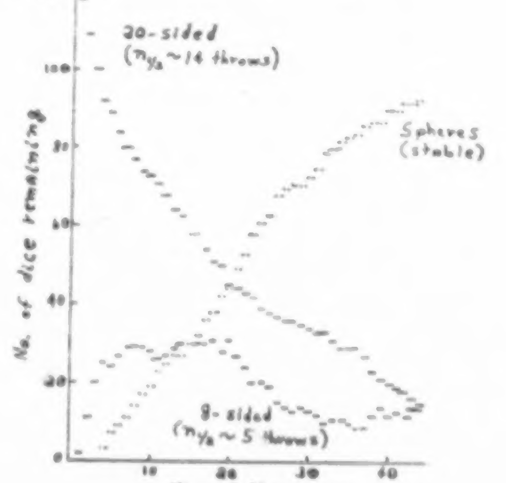


Fig. 4. A typical result obtained in the dice-shaking analogy.

B. Electric circuit. The amount of emphasis placed on the process involved in this part of the experiment will depend on how much students learned about simple electric circuits in Unit 4. If circuits containing resistors in series and parallel have not been studied previously, it will not be worthwhile to introduce them now. But students can still record voltmeter readings as a function of time and see that the resulting graph is a curve which is similar to those obtained from radioactivity and dice.

Students can look for a relationship between R and $T_{\frac{1}{2}}$ if they understand how to compute the resistance of resistors in series and parallel, and if the resistance of the voltmeter is known. A plot of $T_{\frac{1}{2}}$ vs. R should be a straight line.

C. Short-lived radioisotope. At the sink where you have set up the filter flask and pump, place the funnel on the filter flask, shake the bottle containing the slurry of ammonium phosphomolybdate and pour the slurry into the funnel, depositing a layer of the precipitate uniformly over the filter paper to a thickness of about 1 mm. Wash this with distilled water, then pour the thorium nitrate solution slowly, a few drops at a time, over the precipitate. Wash with dilute nitric acid and let the filter pump dry it for a few seconds.

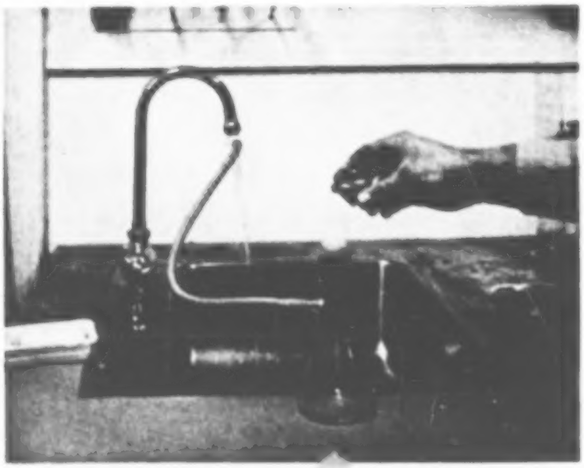


Fig. 5

The Geiger tube supplied by Project Physics is an end-window tube with a diameter less than that of the funnel (See Fig. 6). If you are using this tube it will not be necessary to remove the radioactive sample from the funnel. Instead, wrap a single layer of Saran-Wrap around the tube to avoid contaminating it. Then remove the top part of the funnel and insert the Geiger tube carefully into it until the window is very close to the sample but not touching it. Emphasize to students that the window of the Geiger tube is very thin and fragile.

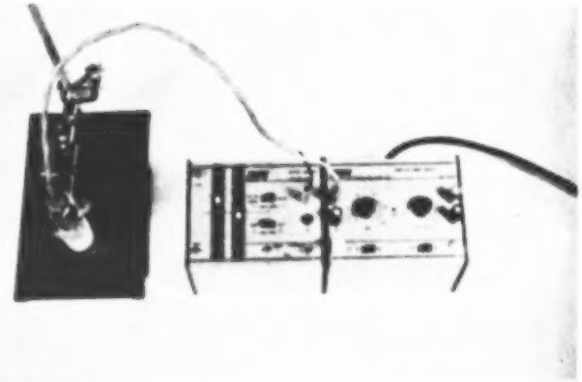


Fig. 6

The radioisotope which is adsorbed from the mixture of thorium daughter products is thallium 208, which has a half-life of 3.2 minutes. If students can count for at least ten half-minute periods, this will include about three half-lives. Again, stress the fact that an exponential curve results when equal fractions decay in equal time intervals.

Discussion

Students should have the opportunity to compare graphs from all three decay experiments. If students have learned about logarithms, have them make a second graph, plotting the logarithm of the quantity which decays as a function of time (or shakes). Alternatively, distribute semi-log graph paper, so that students can come to appreciate the convenience of this kind of plotting. Point out how much easier it is to determine the half-life from the straight line resulting from a semi-log plot.

If two isotopes with differing half-lives are mixed together, the resulting curve will be hard to interpret. In the thallium adsorption experiment, most of the activity in the sample will be thallium 208, with a half-life of 3.2 minutes (plus, perhaps, traces of other elements with much longer half-lives). As a result, a plot of the first 10 minutes (after subtracting background counts) will show a decay curve almost entirely due to the thallium. (The net count rate will level off to a steady value only slightly above zero if the separation has not been quite complete.) A semi-log plot would show a very slight curve rather than a straight line.

Students are asked to apply their knowledge of the relationship $T_{\frac{1}{2}} = \frac{0.693}{\lambda}$, to find the number of dice in a very large tray, given that 50 marked dice appeared on the first shake, and that 4 shakes reduced this number to one half. From this, we find that

$$\lambda = \frac{0.693}{T_{\frac{1}{2}}} = \frac{0.693}{4} = 0.173.$$

But λ is the fraction which "decay" per shake, so $\lambda N = 50$. where N is the number of dice in the tray. Then $N = \frac{50}{0.173} =$ 290 approximately.

The same kind of operation is used to find the half-life of a very long-lived element such as uranium 238 ($T_{\frac{1}{2}} = 4.5 \times 10^9$ years) or thorium 232 ($T_{\frac{1}{2}} = 1.39 \times 10^{10}$ years). The total number of atoms in a sample is determined, then the number of atoms decaying per unit time, $\frac{\Delta N}{N\Delta t}$, is measured. From this $\lambda = \frac{\Delta N}{N\Delta t}$, and $T_{\frac{1}{2}} = \frac{0.693}{\lambda}$.

For example, suppose you have a sample containing 0.1 gram (1.0×10^{-4} kg) of thorium 232, and observe 600 counts per minute, or 10 counts per second. You estimate from the geometry of the counting arrangement that the Geiger tube is actually counting about 2.5 per cent of the atoms which are decaying. The number of atoms in the sample, N, is

$$N = 1.0 \times 10^{-4}\ \text{kg} \times \frac{1\ \text{amu}}{1.6 \times 10^{-27}\ \text{kg}}$$

$$\times \frac{1\ \text{atom}}{232\ \text{amu}} = 2.7 \times 10^{20}\ \text{atoms}.$$

$$\text{Then } \lambda = \frac{\Delta N}{N\Delta t} = 10\ \frac{\text{counts}}{\text{sec}} \times \frac{1}{2.5 \times 10^{-2}}$$

$$\times \frac{1}{2.7 \times 10^{20}\ \text{atoms}}$$

$$= 1.5 \times 10^{-18}\ \text{per sec}$$

$$\text{and } T_{\frac{1}{2}} = \frac{0.693}{\lambda} = \frac{0.693}{1.5 \times 10^{-18}\ \text{per sec}}$$

$$= 4.6 \times 10^{17}\ \text{sec}$$

$$4.6 \times 10^{17}\ \text{sec} \times \frac{1\ \text{yr}}{3.15 \times 10^{7}\ \text{sec}}$$

$$= 1.5 \times 10^{10}\ \text{years}.$$

(The method for separating thallium 208 from thorium has been adapted from an article by John Amend in The Science Teacher, May 1966.)

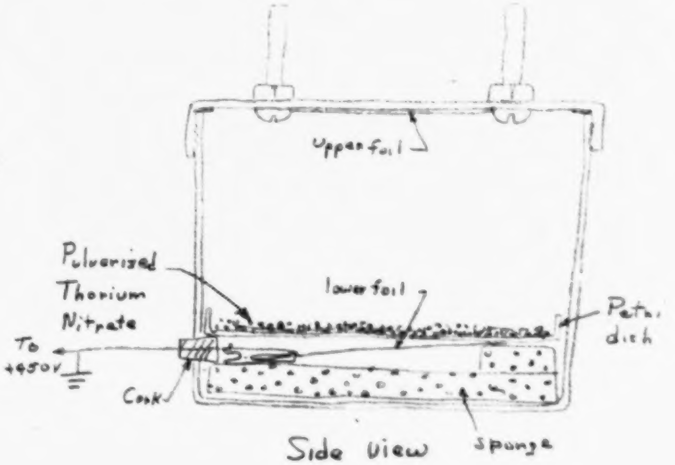
E47 : Half-Life II

The sample used in this experiment is easier to prepare than the thallium 208 used in Experiment 46. On the other hand it has a rather awkward half-life (10.6 hours) which means that counting should be continued over several days. And even if a count is taken early in the morning and late in the afternoon the plot of count-rate against time will have large gaps in it.

Container

Plastic refrigerator jars, ice cream containers, etc., work well. It is easy to make holes in the top and side (try the tip of a hot soldering iron). Use a thinnish disc of sponge rubber at the bottom of the container and moisten it with 10-20 drops of water. (A damp atmosphere increases the amount of deposit collected on the top plate). The top foil (Reynolds Wrap etc.) is held in place by the screws; the lower one is held in the alligator clip.

Spread about 50 grams of pulverized thorium nitrate in a shallow dish (e.g. Petri dish). No special power supply is needed for the high voltage. Use the 450V terminal on the scaler. Make sure that the top foil is at lower potential than the bottom one.



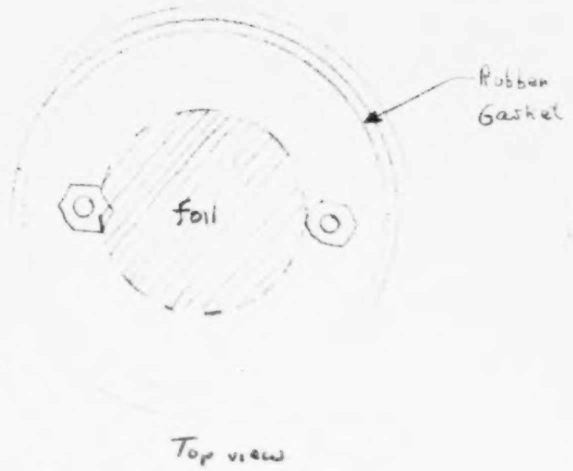


Fig. 1

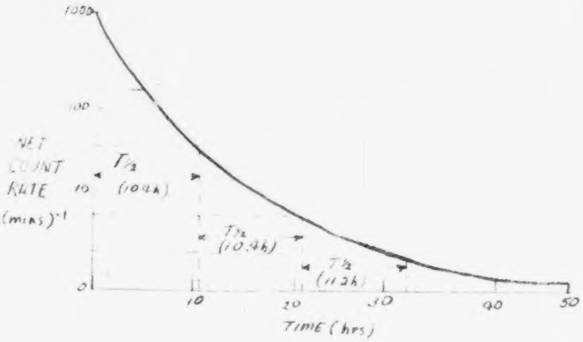
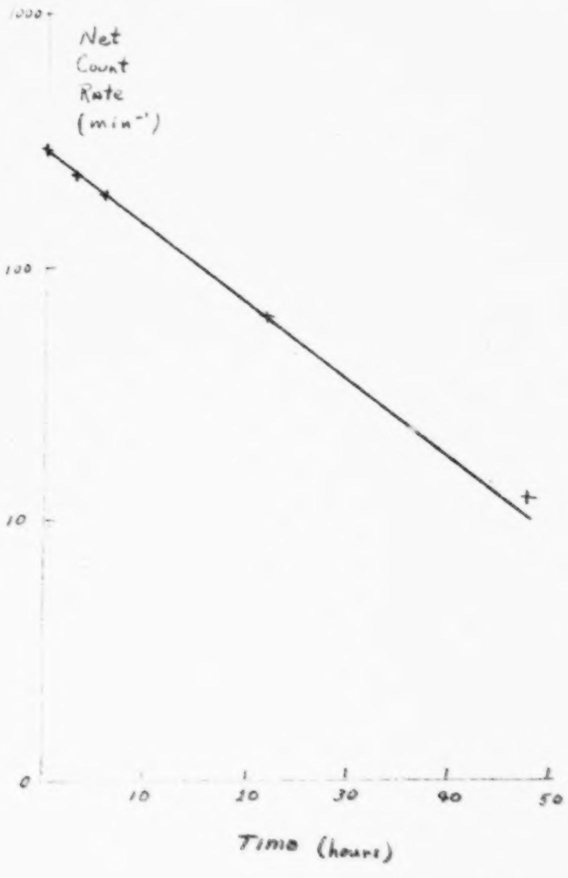


Fig. 2

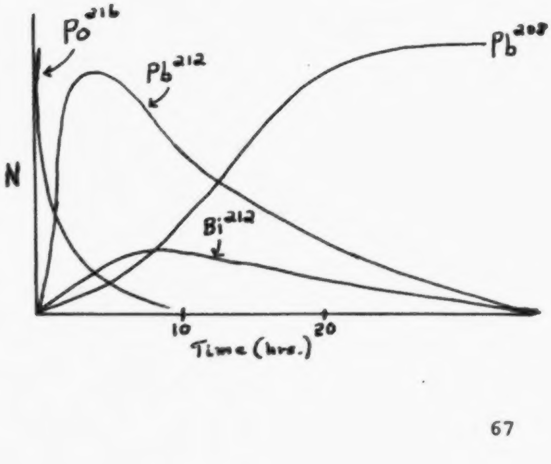
Sample. Let the apparatus stand for about 2 days to get a sample of maximum activity. Turn off the high voltage before removing the lid of the container. If you have several Geiger counters you can cut several samples from each piece of foil—the sample need be only slightly larger than the window of the Geiger tube.



Results. Students will probably report that the sample does have a constant half-life (this is much easier to see on a semi-log plot), in spite of the fact that several isotopes with different half-lives are present in the sample. They should report a value of $T_{1/2} = 10.5$ hours (see Fig. 2)

Po^{216} decays very rapidly ($T_{1/2} \sim 0.16$ sec) Pb^{212}. Pb^{212} has a half-life of 10.6 hours. Although there are three more radioactive daughters before the end of the series (Pb^{208}) is reached, these subsequent isotopes have half-lives much shorter than Pb^{212}. The decay of Pb^{212} is therefore the process that determines the activity of the sample. For a discussion of the activity of a sample containing several members of a decay series see, for instance, Kaplan: Nuclear Physics, Addison-Wesley Publishing Co., 1962.

The student's sketch of isotope concentration vs. time should look something like this:



Since $T_{\frac{1}{2}}$ for Pb^{212} is about 10 hours and is about one hour for Bi^{212},

$$\frac{\lambda Pb}{\lambda Bi} \approx \frac{1}{10}$$

You could make a model of this decay scheme using the multi-faced dice, as in the variation of part A of Experiment 46. Start with 20-sided dice with one face marked ($\lambda = \frac{1}{20}$) to represent the Pb^{212}. Replace each "decayed" atom by an eight-faced die with four faces marked ($\lambda = \frac{1}{2}$) to represent the Bi^{212} atom formed. Replace "decayed Bi^{212} atoms" by balls to represent the stable Pb^{208} atoms. (Make sure you use an ink that can be removed! You will need to have less faces marked for other experiments and in future years.)

Answer to Q2

From Figure 2:

Initial count: 2959 in 10 min

background = 12 per min

$\therefore$ Net count rate = 296-12 - 284/min

Not all disintegrations are detected by the counter. Assume that for our geometry about one-quarter are. Then

$$\left(\frac{\Delta N}{\Delta t}\right)_o \sim 1000/\text{min}$$

$$T_{\frac{1}{2}} = 10.5 \text{ hours (from graph)}$$

$$\therefore \lambda = \frac{0.693}{T_{\frac{1}{2}}} = \frac{0.693}{10.5 \times 60} \text{ min}^{-1}$$

$$= 1.10 \times 10^{-3} \text{ min}^{-1}$$

$$\left(\frac{\Delta N}{\Delta t}\right)_o = \lambda N_o$$

$$\therefore N_o = \frac{1}{\lambda}\left(\frac{\Delta N}{\Delta t}\right)_o \text{ atoms}$$

$$= \frac{1}{1.10 \times 10^{-3}} \times 1000 \text{ atoms}$$

$$\approx 10^6 \text{ atoms}$$

$$\therefore \text{mass of } Pb^{212} = 212 \times 1.7 \times 10^{-27} \times 10^6 \text{ kg}$$

$$= 3.60 \times 10^{-19} \text{ kg}$$

$$= 3.6 \times 10^{-10} \text{ micrograms}$$

Answer to discussion

For the α particle,

$$KE = \tfrac{1}{2} mv^2 = 6.8 \text{ MeV}$$

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{joules}$$

$$\therefore \tfrac{1}{2} mv^2 = 6.8 \times 10^6 \times 1.6 \times 10^{-19} \text{ joules}$$

$$= 1.1 \times 10^{-12} \text{ joules}$$

$$v^2 = \frac{2 \times 1.1 \times 10^{-12}}{m} \text{ (m/sec)}^2$$

$$m = 4 \times 1.7 \times 10^{-27} \text{ kg}$$

$$= 6.8 \times 10^{-27} \text{ kg}$$

$$\therefore v^2 = \frac{2 \times 1.1 \times 10^{-12}}{6.8 \times 10^{-27}} \text{ (m/sec)}^2$$

$$v^2 = 3.2 \times 10^{14} \text{ (m/sec)}^2$$

$$v = 1.8 \times 10^7 \text{ m/sec}$$

(This is considerably less than 3×10^8 m/sec, so we were justified in using the non-relativistic expression $\frac{1}{2}mv^2$ for kinetic energy.)

Momentum is conserved at the collision:

$$(MV)_{\text{Po atom}} = (mv)_{\alpha \text{ particle}}$$

$$\therefore (MV)^2 = (mv)^2$$

$$\frac{1}{M}(MV)^2 = \frac{1}{M}(mv)^2$$

$$\therefore MV^2 = \frac{m}{M}(mv^2)$$

$$\tfrac{1}{2} MV^2 = \frac{m}{M}(\tfrac{1}{2}mv^2)$$

$\therefore$ KE of polonium atom

$$= \frac{m}{M} (\text{KE of } \alpha \text{ particle})$$

$$= \frac{4}{216} \times 6.8 \text{ MeV}$$

$$= 0.12 \text{ MeV}$$

which is very much more than the ionization energy.

A note on safety

For general remarks on radiation safety see the article on page 76 of this Teacher Guide. The fact that we are dealing with a radioactive gas in this experiment may seem to cause an additional safety hazard. A simple calculation shows that there is nothing to worry about.

The amount of radon present is determined by two factors: its rate of formation and its rate of decay.

The rate of decay is about 10^{13} greater than the rate of formation from thorium (10^{10} years: 1 min), so the radon never builds up a high concentration.

The rate of formation is governed by the decay of the parent, thorium 232:

$$\frac{\Delta N}{\Delta t} = \lambda N.$$

For thorium 232

$$\lambda = \frac{0.693}{1.4} \times 10^{10} \text{ years} = 1.58 \times 10^{-18} \text{ sec}^{-1}$$

In a fifty-gram sample there are

$$N = \frac{50 \times 10^{-3}}{232 \times 1.7 \times 10^{-27}} \text{ atoms}$$

$$\therefore \frac{\Delta N}{\Delta t} = \lambda N$$

$$= 1.58 \times 10^{-18} \times 1.25 \times 10^{23} \text{ atoms/sec}$$

$$= 2 \times 10^{5} \text{ atoms per sec}$$

One microcurie is 3.7×10^{4} disintegrations per sec, so the activity here is about 5 microcuries. The decay rate of Rn^{220} is given by

$$\frac{\Delta N}{\Delta t} = \lambda N$$

and $\lambda = \frac{0.693}{51.5} \text{ sec}^{-1} = 1.34 \times 10^{-2} \text{ sec}^{-1}$

$$\therefore \frac{\Delta N}{\Delta t} = 1.34 \times 10^{-2} N \text{ sec}^{-1}$$

The equilibrium concentration of radon, N, is found by setting the rate of formation equal to the rate of decay, i.e.

$$2 \times 10^{5} = 1.34 \times 10^{-2} N$$

$$N \approx 1.5 \times 10 \text{ atoms.}$$

Mass of radon

$$= 220 \times 1.7 \times 10^{-27} \times 1.5 \times 10^{7} \text{ kg}$$

$$= 5.5 \times 10^{-18} \text{ kg}$$

$$= 5.5 \times 10^{-9} \text{ micrograms.}$$

Disposal of waste

At the end of the experiment the activity of the sample will be insignificant, and it can be safely discarded with the trash.

E48: Radioactive Tracers

Little can be said about this experiment, as student responses to such a "blank check" experiment will be varied. You should act as resource person, giving suggestions as to where to find ideas, helping to order isotopes, and seeing that safety precautions are strictly maintained.

As a teacher, you may confront the situation of a student planning an experiment you know will not give a positive result. While negative results are very important in the advancement of science, they may overly discourage a poor student. A confident student, however, might be left alone to pursue such an experiment.

Emphasize to students the possibility of doing a variation of an experiment they read about, beginning with a hypothesis they wish to test, rather than simply repeating an experiment already done.

Students should be encouraged to peruse any literature they can find for possible ideas. The Physics Teacher, The Biology Teacher, Senior Science, Journal of Chemical Education, Scientific American (e.g. May 1960) occasionally have tracer experiments. A number of useful sources are listed at the end of the student instructions, and others of interest to teachers are listed below. Whether or not any of the listed sources are available, one can fall back on John H. Woodburn's article, Low-Level Radioisotope Techniques, printed elsewhere in this guide.

To do the simple autoradiograph experiment a radioactive source is needed. One simple possibility is a lump of uranium ore from a mineral supply company such as The Foote Mineral Company, 18 W. Chelton Avenue, Philadelphia 44, Pa.; OR Wards Natural Science Establishment, Rochester, New York.

Once an experiment has been chosen, you should discuss what safety precautions will be necessary. Refer to a summary of these elsewhere in the Teacher Guide.

Finally, you will need to order the isotopes students will need, as suppliers will not usually ship to minors. Choose the nearest supplier from the supplier's list, and write well in advance in order to check on his shipping procedures. Then when the experiment is ready, the order can be placed at the advance interval specified by the supplier. For example, many suppliers ship on Fridays to be received the following Mondays at the specified strength.

In addition to the articles listed in the Student Handbook, the following books and articles may be of use to teachers.

"Nuclear Science Teaching Aids and Activities," J. Woodburn and E. Obourn. U.S. Office of Education. Available at no cost from Superintendent of Documents, Government Printing Office, Washington, D.C. 20402.

"Radioisotope Experiments for the Chemistry Curriculum," Teacher's manual. $1.00 See corresponding title in student references.

Radioactive Tracer Research, M.D. Kamen, Holt, Rinehart, and Winston, Inc., 383 Madison Avenue, New York, N.Y. 10017. $1.60 paperback.

Isotopes in Action, D. Harper. Pergamon Press, Inc., 44-01 21 Street, Long Island City, N.Y. 11101. $2.95

"Power from Radioisotopes," "Radioisotopes in Industry," "Radioisotopes and Life Processes," and "Radioisotopes in Medicine," a series of pamphlets for the general reader available at no cost from the U.S. Atomic Energy Commission, P.O. Box 62, Oak Ridge, Tennessee 37830.

"Tracers," M.D. Kamen, Scientific American, February 1949; and "Radioactivity and Time," P.M. Hurley, Scientific American, August 1949. Reprints of these two articles at 20 cents each available from W.H. Freeman and Company, 660 Market Street, San Francisco, California 94104.

Note also the article "Low Level Radioisotope Techniques," by John Woodburn, and the numerous references to articles on radiation safety reprinted elsewhere in this Teacher Guide.

NOTE: Pages 71-73 refer to equipment produced for 1967-68. Appropriate new equipment notes will be provided with new equipment by DAMON.

Scaler/Counter

The Scaler/Counter (DEC-100) is one of the series of compatible electronic units produced for Project Physics. It can be used:

a) as an event counter—e.g. in conjunction with a Geiger tube.
b) as an interval timer—using an internal 120 cycle (line frequency) source.

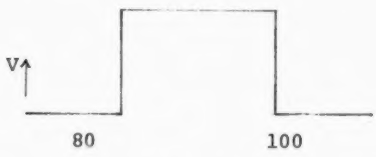
It is used with the Amplifier (Power-Supply unit APS-100) which both amplifies the signal to be counted and supplies power to operate the counter. The DEC-100 can operate at up to 2×10^6 per second. The highest count rate you are likely to encounter in Project Physics work (in the Thallium-208 experiment) is less than 6000 per minute.

Each signal pulse (from Geiger tube) or cycle of 120 signal causes the count shown on the scaler to change by one.

Controls

÷ 100 Output

When both decades are full (count of 99) the best input signal returns the count to zero. At this time a 1-2 volt pulse is produced at the ÷ 100 output. A loudspeaker, or voltmeter, or oscilloscope connected between this output and ground can be used to detect the pulse. This pulse is actually a square pulse that goes positive when the count reaches 80 and back to zero at 100. A double blip will therefore be heard in the loudspeaker at low count rates. These blips are not very loud and need to be listened for quite carefully.



Students can record manually these ÷ 100 pulses at up to about one per second, corresponding to a count rate of about 100 per second (6000 per minute).

None of these output devices are actually essential. Students can simply watch the numbers changing and record a count of one hundred every time the count goes from 99 to zero.

If you need to count at more than 6000 per minute you could -

a) feed ÷ 100 pulse into a second decade scaler,
b) use the ÷ 100 pulse with a relay to operate a mechanical register.

450 V DC Output Jack

The 450 volt dc output (for Geiger tube) has a 10K ohm series resistor to limit the current temporarily if the supply is shorted, but the supply must not be shortedindefinitely.

Reset Button

This returns the count to zero. Counter does not operate properly unless this is pressed when the unit is first turned on, or a new input is applied.

Hold Mode Switch

When set to GATE the counter stops counting while the MANUAL HOLD button is held depressed.

If the HOLD MODE is set to PULSE the counter starts when the MANUAL HOLD button is depressed and released and stops when the button is depressed and released again.

Electronic Hold Jack

Allows external (automatic) switching. Shorting the ELECTRONIC HOLD jack to ground is equivalent to depressing the MANUAL HOLD button and can be used in either "gate" or "pulse" mode. A mechanical switch could be used. A useful alternative is a photoconductor (conducts better when illuminated than when dark). For details and applications see "Timing Intervals" below.

Count Input Switch

Set to the "120 H_z" position for interval timing. The count changes by one unit every 1/120 sec = 0.0083 sec.

Set to the APS-100 output position to count pulses from Geiger tube or other source. See "Operation," below for details.

Operation

Plug Scaler/Timer unit (DEC-100) into Amplifier/Power-supply (APS-100). Turn on APS-100.

a) Geiger tube. Connect the Geiger tube between the 450 V dc output on the scaler and the amplifier input.
Set COUNT INPUT to the APS-OUTPUT position.
Set HOLD MODE to GATE.
Set DC OFFSET control to -1 volt.
Press RESET button.

With a source near the Geiger counter turn up the GAIN control of APS-100 until the counter begins to operate. A setting of 10-20 should be adequate. Too high a setting may cause suprious counts due to pickup. Check this by observing count rate with no source near counter. The count rate should be about 10-20 per minute, except in regions where the background count is exceptionally high.

Equipment Notes
Geiger Tube
Cadmium Selenide Photocell

When using the scaler to count pulses from a Geiger tube it is probably most convenient to work with the HOLD MODE switch at PULSE. Press and release the MANUAL HOLD button to start the count; press and release again to stop. Record the count, press and release the RESET button. Press and release MANUAL HOLD button to start the next count, and so on.

The various ways of coping the ÷ 100 output are discussed above.

For more information on the Geiger tube itself see the Equipment Note: Geiger Tube.

b) Interval Timer. With the scaler plugged into the Amplifier/Power-supply, no input to the amplifier (the Geiger tube disconnected), and the amplifier/power-supply turned on –

a) Set COUNT INPUT to "120 H_z".
b) Set HOLD MODE to GATE.
c) Press and release RESET button.

The counter will now be counting at 120 counts/sec. Each count represents 1/120 = 0.0083 sec. and a one volt pulse will appear at the ÷ 100 output every 0.83 sec.

The counter will stop when the MANUAL HOLD button is depressed, start again when it is released. The RESET can be operated while HOLD is held down.

d) If the HOLD MODE is set to PULSE, the counter will start when the MANUAL HOLD is pressed and released and go on counting until it is pressed and released again. Operate RESET between counts.

An external mechanical or photo-conductive switch can be used (see "ELECTRONIC HOLD" above). This is particularly useful for short time intervals.

For example: Connect a photo-conductive cell between the -6V DC terminal on the APS-100 and ELECTRONIC HOLD on DEC-100.

Set HOLD MODE to GATE. Illuminate the cell so that the counter does not operate when light falls on the cell, does operate when the light beam is interrupted. With the HOLD MODE set to gate the counter will record the time for which the beam is interrupted: e.g. the time it takes a falling object to pass in front of the cell (from this and the object's size you can calculate velocity); OR - set up two photocells and illuminate by a light beam and connect the two in parallel between -6V and ELECTRONIC HOLD. Set the HOLD MODE switch to PULSE. The counter will now start when the first light beam is interrupted and stop when the second beam is cut off.

Similar automatic mechanical arrangements could be set up—e.g. two wires that are connected when a metal ball falls between them.

c) External Oscillator. Instead of the internal 120 cycle oscillator. Connect the oscillator to the input terminal of the amplifier, set COUNT INPUT to APS-100-OUTPUT, DC OFFSET to -1 volt and gain to about 20 (as for Geiger tube—above).

Press reset button. The counter will record all the pulses applied to the amplifier input.

Geiger Tube

The Geiger Tube is an Amperex 18504 end window (3 mg/cm^2) halogen quenched tube. The thin end window is made of mica: it is most fragile and must not be touched. When the tube is not in use, protect it with the plastic cap provided. When using the tube in Experiment 46 (half-life of Thallium) wrap a single layer of plastic (saran wrap) around it to prevent permanent contamination of the tube.

Cadmium Selenide Photocell

This photocell is to be used in conjunction with the new SCALER/TIMER unit to measure short time intervals and hence velocities—in Unit 1 of the course.

The photocell is a cadmium selenide photo conductive cell. Its dark resistance is at least 50 Megohms, in normal room lighting ~1 megohms and in stronger illumination e.g., in flashlight beam or in the beam produced by the light source of the Millikan apparatus, its resistance falls to ~1000 ohms.

OBJECTS DATED BY RADIOCARBON

Linen wrapping from the Dead Sea Scroll containing the Book of Isaiah. 1917 ± 200 years old.

Rope sandal found in an eastern Oregon cave. One of a pair of 300 pairs found in this cave. 9035 ± 325 years old.

Hair of an Egyptian woman. 5020 ± 290 years old.

BASIC MEASUREMENT METHODS

Method	Material	Time Dated	Useful Time Span (years)
Carbon-14	Wood, peat, charcoal	When plant died	1000-50,000
	Bone, shell	Slightly before animal died	2000-35,000
Potassium-argon	Mica, some whole rocks	When rock last cooled to about 300°C	100,000 and up
	Hornblende Sanidine	When rock last cooled to about 500°C	10,000,000 and up
Rubidium-strontium	Mica	When rock last cooled to about 300°C	5,000,000 and up
	Potash feldspar	When rock last cooled to about 500°C	50,000,000 and up
	Whole rock	Time of separation of the rock as a closed unit	100,000,000 and up
Uranium-lead	Zircon	When crystals formed	200,000,000 and up
Uranium-238 fission	Many	When rock last cooled	100—1,000,000,000 (Depending on material)

Preglacial wood found in Ohio. More than 20,000 years old.

Peruvian rope. 2632 ± 200 years old.

Radiation Safety

(Based on material supplied by Oak Ridge Associated Universities)

Many schools, including those adopting Harvard Project Physics, are incorporating some form of radioisotope work into their science curriculum. As a result of this, questions concerning the potential hazards and control of radiation are bound to be raised by teachers, students and parents. It is the purpose of this article to deal as briefly as possible with such questions and to provide the information that will be necessary for the safe introduction of radioisotopes into the high school course.

MEASUREMENT OF RADIOACTIVITY

The basis of all measurements of radioactivity is the creation of an ion-pair by radiation.

The most common units used for measuring radioactivity and radiation exposure are the curie, the roentgen, the rad, and the rem. Each unit indicates a different quantity which is of interest to the scientist.

CURIE (Ci) - A unit used to measure the rate at which radioactive material, or a combination of radioactive materials, is giving off nuclear particles. One curie = 37,000,000,000 disintegrations per second (dps). Since it is the number of disintegrations per second which determines the amount of radiation emitted, the activity of the source is a significant factor. However, the type and energy of the radiation are also important in evaluating the potential hazard, and the curie does not measure this. The curie is not a measure of exposure to radiation damage.

The curie is a very large amount of radioactivity. Historically, the unit was chosen because it was approximately the amount of radiation emitted by 1 gram of pure radium. More practical units for laboratory use are the millicurie (mCi) or 10^{-3} curies, and the microcurie (μCi), or 10^{-6} curies.

ROENTGEN (R) - The roentgen is a unit of exposure dose. It measures the ionization in air produced by a source of gamma or x rays. One roentgen produces 2.58×10^{-4} coulombs of charge (about 1.6×10^{15} ion pairs) per kilogram of dry air. This unit is not applicable to such particle radiations as alphas, betas and neutrons. Radiation survey instruments are usually calibrated in R/hr or mR/hr.

RAD - The rad is the unit of absorbed dose. It amounts to 100 ergs (10^{-5} joules) of energy imparted to a gram of irradiated material, by any ionizing radiation.

REM - The rem was devised to make allowance for the fact that the same dose in rads delivered by different kinds of radiation does not necessarily produce the same degree of biological effect; some radiations are biologically more effective than others. The rem may be thought of as an abbreviation for radiation effect, man. Since various radiations such as alpha, beta, gamma rays and neutrons have different biological effects per RAD of absorbed energy, they are assigned values depending on the biological effect being considered. For a given biological effect, the number of REMS = RADS × RBE.

The relationships among the units of radiation exposure as they apply to the radiation of water and soft tissue are summarized in the following table (1):

Type of Radiation	R	rad	rems (or QF)
X-rays and Gamma-rays	1	1	1
Beta particles	-	1	1
Fast neutrons	-	1	10
Thermal neutrons	-	1	4-5
Alpha particles	-	1	10

Table 1: Relationships among radiation units

Since the human body is about two-thirds water, this table provides a means for making a rough estimate of the biological effect of simultaneous or consecutive absorption of different kinds of radiation.

RADIATION PROTECTION GUIDELINES:

Nuclear radiations are a natural part of man's environment, just as are the sunlight and the earth's magnetic field. Man has always lived in an environment that includes a great deal of natural radiations. In addition, we have created new sources of radiation as we have explored nature and hunted for ways to improve our control and use of nature. Natural radiation comes from both the earth and the sky. Such radioactive minerals as uranium and thorium, and decay products associated with them, exist everywhere in the earth. The places where they are mined are simply the locations of extremely large concentrations of these minerals. The radioactive gas radon is present in small amounts in the air we breathe. Cosmic radiation—particles of very high energy—which strike the earth's atmosphere from outerspace, contributes both directly and indirectly to the amount of radiation to which we are exposed. Cosmic rays contribute directly by striking our bodies, ionizing body materials, which causes radiation damage. They contribute indirectly by creating radioactive carbon-14 when cosmic neutrons strike atmospheric nitrogen. C^{14} is then quickly converted into $C^{14}O_2$. The $C^{14}O_2$ is utilized by plants in photosynthesis and the plants are eaten by animals. The radioactive carbon eventually finds its way into our bodies through our food. In fact, the disintegration of C^{14} causes the liberation of about 200,000 beta particles per minute in the average adult. K^{40} which is also in our bodies, liberates approximately 240,000 beta particles per minute in the average adult. Other radioactive materials in our bodies include radium-226, strontium-90, cesium-137 and iodine-131

It is true that all radiation is harmful, but it is also true that human beings can be, and in fact are continuously exposed to radiation at low intensity without any apparent harmful effects. Body tissue is both damaged and destroyed whenever one cuts himself, bruises himself, or breaks a bone. But just as the body is able to adjust to this type of an injury and mend the damage, so it is able to adjust to and counteract the harmful effects of small doses of radiation. Similarly, large doses of radiation can cause severe injury and even death just as many other types of injuries can.

Sources of man-made radiation which contribute to our total exposure to radiation include x rays, radioactive fallout, luminous watch dials, television tubes, radioactive industrial wastes, etc.

It is estimated that the average annual exposure in the United States amounts to 267 millirems. Natural sources (cosmic radiation, minerals, etc.) contribute 101 millirems and man-made sources, mostly from medical x rays, make up the remaining 166 millirems. Radioactive fallout accounts for 4 millirems.

One of the questions health physicists are called upon to answer is what are the safe and maximum permissible radiation exposures that one can receive. To answer a question of this type, it must be understood that the effects of radiation exposure depend on several factors. These include:

1. The amount and rate of radiation exposure.

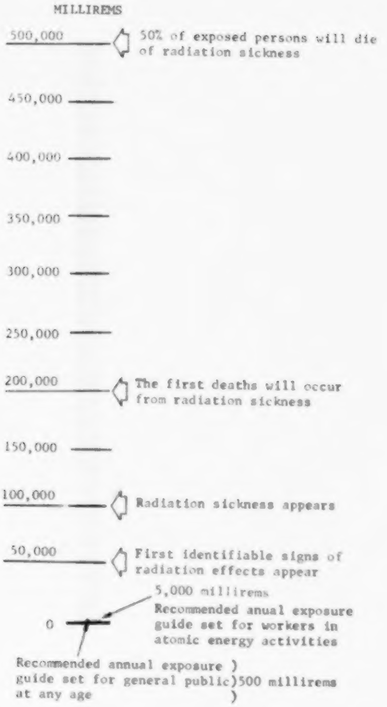
2. The kind of radiation—whether it is penetrating radiation such as gamma rays and x rays, or relatively nonpenetrating such as alpha particles.

3. The tissue exposed, which depends in turn on the source of the exposure—whether the radiation came from outside the body or from radioactivity inside the body.

4. The kind of radioactive material involved, its radioactive and chemical nature, and its biological path if taken into the body (2).

Balancing the risks involved in radiation exposure against the benefits to be gained from increased knowledge, the National Committee (now Council) on Radiation Protection and Measurements (NCRP) and the International Commission on Radiological Protection have set limits on what is considered an acceptable exposure for persons occupationally exposed to radiation. These limits are in addition to background and medical and dental exposures. The primary goal is to keep radiation exposure of the individual well below a level at which adverse effects are likely to be observed during his lifetime. Another objective is to minimize the incidence of genetic effects.

Figure 1 shows the recommended limits of exposure on a chart which relates exposure to biological effects.


MILLIREMS
500,000
50% of exposed persons will die of radiation sickness
450,000
400,000
350,000
300,000
250,000
200,000
The first deaths will occur from radiation sickness
150,000
100,000
Radiation sickness appears
50,000
First identifiable signs of radiation effects appear
5,000 millirems Recommended anual exposure guide set for workers in atomic energy activities
0
Recommended annual exposure guide set for general public at any age) 500 millirems

Note that the exposure guide set up for workers in atomic energy activities is one tenth of the level at which the first identifiable signs of radiation effects occur. The exposure guide set for the adult general public is just about twice the average background level due to natural and man-made sources. It is one-hundredth of the level at which the first identifiable signs appear.

By adhering to the guidelines that have been set, industries engaged in atomic energy activities in the United States have insured that the risk of damage to exposed persons is not greater than the risks normally accepted in other present-day industries. In fact, the safety record of these industries is the best in the nation.

The following additional limits apply to the high school situation (3):

1. Students under 18 years of age who are exposed to radiation during educational activities should not receive whole body exposures exceeding 0.1 rem per year. To provide an additional factor of safety, it is recommended that each experiment be so planned that no individual receive more than 0.01 rem while carrying it out.

It should be emphasized that there is no difficulty in performing radiation experiments and demonstrations in conformity with the above recommendations, if appropriate safeguards are taken. These appropriate safeguards are discussed in the following sections.

2. Persons under 18 years of age shall not be occupationally exposed to radiation. (They shall not be employed or trained in an x ray department, radioisotope laboratory, or industrial radiation facility.)

EXTERNAL HAZARD CONTROL

1. Quantity and Type of Radiation Source:

Because each radioisotope has its own characteristic mode of decay, equal activities (curies) of different radioisotopes may provide different exposure rates (roentgens). Radiation safety is concerned with limiting exposures, so control deals with limiting the amount of isotope used to the minimum necessary to achieve the desired results and the careful selection of isotopes according to the exposure rate they produce.

2. Distance:

The easiest means of controlling radiation exposure is to use the fact that radiation intensity follows an inverse square law.

3. Length of Exposure:

The total exposure that a person receives is the product of the exposure rate and the length (time) of exposure:

$$I \times T = \text{total exposure}$$

where: I = exposure rate, R/hr
T = length of exposure.

Radiation safety requires that the product of length of exposure and exposure rate not exceed the recommended limits. Figure 2 shows this relationship. For high exposure rates, only very short exposure periods are allowed, though very long exposure periods are permitted at very low exposure rates.

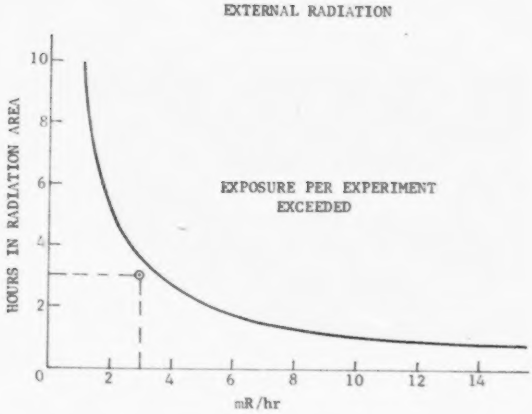


Fig. 2 The recommended maximum exposure is 10 mR per experiment for students under 18 years of age. A three-hour exposure at 3 mR/hr does not exceed the recommended level.

4. Shielding:

For sources of radiation either very large in quantity or in size, it is not always possible to achieve the degree of radiation safety required by using the first three factors alone. The use of some type of shielding is required. The type of shielding used depends on the type of radiation to be absorbed.

The rate at which alpha particles lose energy is so great that even a millimeter of any solid or liquid material will stop the alpha particle. Hence, alpha particles are not usually considered an external radiation hazard because their penetration in tissue is only a fraction of a millimeter. As a result, they expend all their energy in the dead (cornified) layer of skin which covers the body.

Beta particles (having less mass and charge and a much greater velocity than alpha particles) are more penetrating but also have a limited range. The following figure shows the range of beta particles of various energies in different materials (Fig. 3).

Note that while the range of betas in air may be as much as a meter, the range in a material such as glass is a fraction of a millimeter. Beta and alpha particles are, therefore, easily protected against, with relatively thin shields.

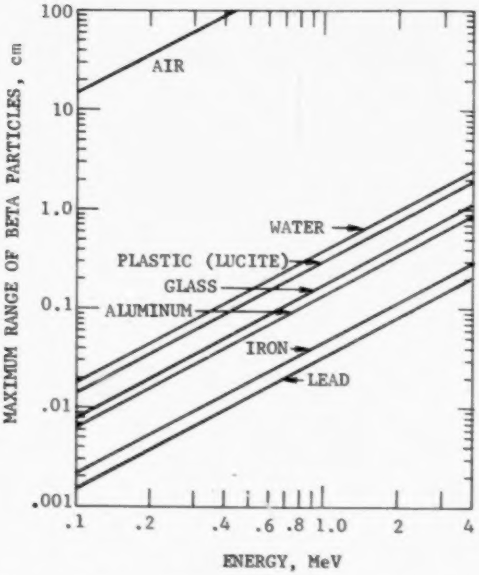


Fig. 3 Range of beta particles as a function of energy.

The absorption of gamma rays by matter, like the absorption of light, follows a negative exponential law:

$$I = I_o e^{-\mu x}.$$

$$\text{So } \ln \frac{I}{I_o} = -\mu x \text{ or } \log \frac{I}{I_o} = -0.434\mu x.$$

where: I_o = exposure rate at a given point with no shielding
I = exposure rate at the same point but with a shield of thickness x between source and point where intensity is measured
x = thickness of shield
μ = linear attenuation coefficient.

The relationship between I and x is not linear, but use of the equation will enable one to determine the thickness of lead required to reduce the intensity to the desired level.

Theoretically it is not possible to attenuate gamma radiation completely, but the exposure rate can be reduced by any desired factor. A useful concept regarding gamma attenuation is the half-value layer (HVL) or the half thickness $x_{\frac{1}{2}}$ which is defined as the thickness of any particular material necessary to reduce the intensity of a beam of x-rays or gamma-rays to one-half its initial value. Similarly the tenth-value layer (TVL) or the tenth thickness $x_{1/10}$ is defined as the thickness of any particular material necessary to reduce the intensity of a beam of x-rays or gamma-rays to one-tenth its initial value. Hence, three tenth-value layers will reduce the dose received from a gamma source to 1/1000 of the initial amount (1/10 × 1/10 × 1/10).

Approximate Half- and Tenth-Value Layers for Gamma-rays

Material	Water		Aluminum		Iron		Lead	
Gamma energy (MeV)	HVL $x_{1/2}$ (cm.)	TVL $x_{1/10}$ (cm.)	HVL $x_{1/2}$ (cm.)	TVL $x_{1/10}$ (cm.)	HVL $x_{1/2}$ (cm.)	TVL $x_{1/10}$ (cm.)	HVL $x_{1/2}$ (cm.)	TVL $x_{1/10}$ (cm.)
0.20	5.2	17.3	1.9	6.3	0.66	2.20	0.14	0.47
0.50	7.2	24.0	3.0	10.0	1.11	3.70	0.43	1.43
1.0	9.8	32.6	4.1	13.7	1.56	5.20	0.88	2.93
1.5	12.2	40.6	5.1	17.0	1.74	5.80	1.17	3.90
2.0	14.0	46.6	5.9	19.7	2.05	6.83	1.37	4.57
2.5	15.8	52.6	6.7	22.3	2.22	7.40	1.47	4.90
3.0	17.4	58.0	7.2	24.0	2.31	7.70	1.51	5.03
4.0	20.0	66.7	8.4	23.0	2.55	8.50	1.48	4.93
5.0	22.1	73.7	9.4	31.3	2.88	9.60	1.42	4.73

We can see from this table why lead is so often used as a shield for radioisotopes.

Shield Material	Gamma-Ray Energy 0.1 MeV	0.5 MeV	1.0 MeV
Water	0.17	0.097	0.06
Iron	2.7	0.66	0.55
Lead	62	1.7	0.79

Linear attenuation coefficients (cm^{-1})

Fig. 4 shows the relationship of I to x for lead. Because of its high value of μ, lead is often used as a shielding material.

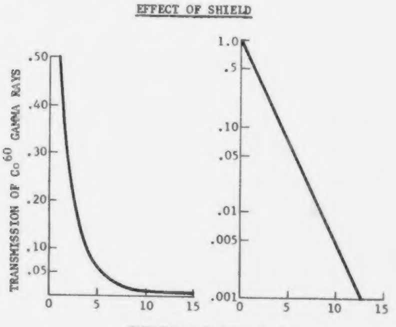


Fig. 4

(a) Linear graph (b) Semilog graph

INTERNAL RADIATION HAZARD

Any radioactive substance entering the body is hazardous. Commonsense rules can prevent radioisotopes from being ingested. They are:

a) Never place any materials used in the laboratory in the mouth. Pipetting, glass blowing, etc., should be done using indirect methods. (Various inexpensive types of pipettors are available on the market.)

b) Never handle radioactive materials directly. Always use rubber or plastic gloves, tweezers or some means of indirect contact.

c) Do not eat, smoke or apply cosmetics in areas where radioisotopes are handled.

d) Never place your hands near your face or mouth while working with radioisotopes.

e) When working with liquid sources always cover your working area with absorbent material, preferably inside a tray, to retain any spilled liquid.

f) At the end of an experiment check all tools, glassware, etc., with Geiger counter. Wash your hands carefully.

RADIONUCLIDE SOURCES

The most commonly used naturally occurring radioactive substances with sufficient activity to constitute a possible hazard are radium, polonium, actinium, thorium, and uranium. Of these, radium and polonium are particularly significant since they are readily available and are frequently used in quantities sufficient to constitute a potentially serious radiation hazard. Also, uranium and thorium salts can be purchased from chemical supply houses by the case and shipments generally are delivered without any radiation warning signs on the bottles. Although these salts are no real hazard in terms of external radiation, they could be a potential internal radiation hazard and should be treated as such.

Note: Normal uranium and thorium, in soluble form, are more dangerous as chemical poisons inside the body than as sources of radiation, since relatively large quantities are required to cause severe radiological damage.

Artificially produced radionuclides are produced either by the fission of heavy elements in a nuclear reactor or by the bombardment of non-radioactive isotopes in high-energy accelerators or nuclear reactors. Over a thousand radionuclides are known, and of these, about one hundred are in common use. Small amounts of certain commonly used nuclides are available without specific license. Acquisition of larger amounts of nuclides requires a specific license from the Atomic Energy Commission or State regulatory agency, or from both.

THE PROVISION FOR AND THE USE OF "GENERALLY LICENSED" RADIOISOTOPES IN THE HIGH SCHOOL CLASSROOM

The quantity of radioisotopes used in the high school classroom is usually limited to very small amounts that are generally licensed by the Atomic Energy Commission. A partial listing of these (termed "generally licensed" by the AEC, "exempt" by states, and "license free" by some suppliers) is given in the Survey of Commercially Available Radioactive Sources (p. 88). A teacher may purchase any of these radioisotopes without fulfilling any specific licensing requirements provided that he or she does not at any one time posses or use more than a total of ten such quantities. Although generally licensed quantities may be purchased without the need of any specific license from the AEC, the user is not exempt from adhering to the regulations that are concerned with their use; hence, it is recommended that teachers obtain copies of these regulations (6).

"Generally licensed" quantities of materials in solution cannot be added together to obtain a source of a higher activity. If higher activities are desired, proper authorization must be obtained for their acquisition. Hence, if a teacher wants a 30μCi source of P^{32}, he cannot buy three 10μCi liquid sources and pour them all together.

The limitation of quantity by the Atomic Energy Commission practically assures the safety of the persons using or coming in contact with radioisotopes in the high school program. However, the fact that they are radioactive materials and can constitute a safety hazard should always be kept in mind and the methods of controlling both external and internal hazards should become a part of both the student's concern as well as the concern of the teacher.

For any gamma-emitting radionuclide the specific gamma ray constant is the exposure rate in roentgens per hour for a point source of 1 millicurie at a distance of 1 centimeter. Values of this constant are listed in Table 6 for certain gamma emitters. If used as gamma sources, beta-gamma emitters can be enclosed in a sufficient thickness of glass, plastic, or metal to eliminate essentially the beta radiation (see Figure 3). As stated earlier, both beta and gamma radiations are capable of producing biological effects.

A "generally-licensed" or "exempt" source, when used for a short time such as one or two hours, represents a negligible external hazard. However, if it were to be kept close to the skin for many hours, injurious effects could possibly be produced. Radiation sources should, therefore, not be carried in pockets or handled without proper tools. Adequate precautions should be taken to prevent radioactive materials, irrespective of amount, from gaining entry to the body, e.g., through the mouth, the nose, or the skin (3).

Just about any laboratory exercise involving the use of radioisotopes to be done at the high school level can be accomplished using "generally licensed" quantities of radioactive materials. A few exceptional cases may arise, but in the vast majority of cases, the "generally licensed" quantities will suffice. As a rule of thumb in choosing radioisotopes to be used in a classroom experiment, choose the source of minimum strength (activity) required to perform the experiment.

Records should be kept of all radioactive materials that have been and are being used in the classroom. The records should contain the name of the isotope, the activity, the specific gamma constant, if it is a gamma emitter, the half life, the date of shipment, the storage location, the names of persons using the isotope, and the date of disposal.

CALCULATION OF RADIATION EXPOSURE

In an experiment to study the absorption of gamma rays by lead sheets, some high school students will be using a new 1 μCi Co^{60} plastic sealed disc source. Since 1 μCi is only one-tenth of the maximum amount of Co^{60} that may be purchased as a generally licensed quantity in the form of a sealed source, it may be considered safe for student use under ordinary conditions. However, if a teacher desires to determine what doese in rems a student will receive from this source if the student were sitting, on the average, about 20 cm from the source during the experiment which takes about 30 min., he could proceed as follows:

$$\text{Dose (rem)} = \begin{pmatrix}\text{Specific}\\ \text{gamma ray}\\ \text{constant}\end{pmatrix} \times \text{Present activity of source} \times \text{time of exposure (hr)} \times \frac{1}{(\text{dist. in cm})^2} \times 1\,\frac{\text{rem}}{\text{roentgen}}\,.$$

For Co^{60},

$$\text{Dose} = 12.9\,\frac{\text{roentgen}\cdot\text{cm}^2}{\text{mCi}\cdot\text{hr}} \times 1\ \mu\text{Ci} \times 10^{-3}\,\frac{\text{mCi}}{\mu\text{Ci}} \times 1/2\ \text{hr} \times \frac{1}{(20\ \text{cm})^2} \times 1\,\frac{\text{rem}}{\text{roentgen}} \simeq 1.6 \times 10^{-5}\ \text{rem}\,.$$

This exposure is well below the 0.01 rem/experiment maximum which was suggested earlier.

Also, since 0.01 rem/experiment is the recommended maximum, no student should work in an area where a survey instrument reads above 10 mR/hr. (Note: survey instruments are often available from local Civil Defense authorities.)

RADIATION WARNING SIGNS

All radiation sources should be identified by the standard radiation symbol.

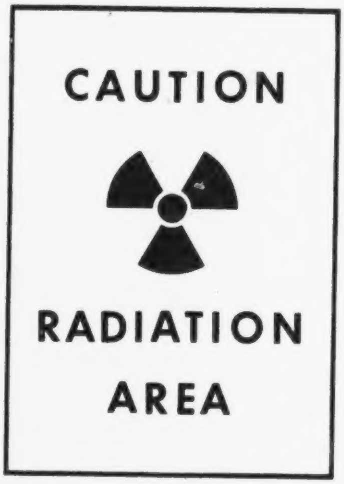


Fig. 5 The Standard Radiation Symbol

Besides warning of the presence of radioactive material, the warning sign should also indicate the person responsible for the material and how he may be contacted.

STORAGE OF RADIOACTIVE MATERIALS

All radioactive materials should be stored in a plainly marked and properly shielded area. The area should be secured against the unauthorized removal of radioisotopes from the place of storage. All radioactive materials should be signed for on removal and checked back in on their return so that the whereabouts of the materials is always known. The activity immediately outside the storage area should not be above background.

WASTE DISPOSAL

The following general rules apply:

1. The Code of Federal Regulations, Title 10, Part 20 or comparable State Regulations should be consulted for detailed information on the proper disposal of quantities of liquid source materials which exceed the quantities that are termed generally licensed. (See also NCRP Report No. 30.)

2. When work with generally licensed quantities of liquid sources has been completed, they may be disposed of in the sanitary sewer system, if flushed away with a considerable amount of extra water.

3. The final disposal of solid radioactive waste may require the use of a licensed commercial disposal service. If there is doubt, a radiological physicist, a health physicist, or the local health agency should be consulted.

4. Solid sources of short-lived isotopes may be stored for decay to possibly 1/10 of the permissible exempt value, and then disposed of, singly, in the ordinary trash (8).

5. Never throw long-lived solid radioactive wastes into the ordinary trash receptacles. You have no control over their final destination.

Some question may arise as to the method of disposal of various uranium and thorium salts which have been placed in solution. The method is probably best illustrated by an example.

Example: In the half life of Tl^{208} experiment that is used in Harvard Project Physics, an acidic solution of thorium nitrate is prepared by dissolving 5 grams of thorium nitrate in 10 ml of 2 molar nitric acid. During the course of the experiment, the solution is further diluted with another 10 ml portion of 2 molar nitric acid. The end result is that for each lab group, the instructor is faced with the problem of safely disposing of a solution of 5 grams of thorium nitrate dissolved in 20 ml of liquid. How can safe disposal be accomplished?

Procedure:

Thorium nitrate: $Th(NO_3)_4 \cdot H_2O$

F.W. = 552.146

Grams of thorium in a 5 gram sample

of thorium nitrate $= 5\frac{(232)}{552.146)} = 2.1$ gm.

Activity of the Th^{232} sample:

Act. = (mass of Th^{232})(Specific Activity of Th^{232})

$= (2.1 \text{ gm})(1.11 \times 10^{-7} \frac{\text{Ci}}{\text{gram}})(10^{6} \frac{\mu\text{Ci}}{\text{Ci}})$

$= 2.33 \times 10^{-1}$ μCi.

The radioactivity concentration guide permits a concentration Th^{232} in water $\leq 5 \times 10^{-5}$ μCi/ml.

(From Appendix B of Title 10, Ch. 1, Part 20 of the Code of Federal Regulations.)

Dilution factor:

$2.33 \times 10^{-1} \mu\text{Ci}/5 \times 10^{-5} \frac{\mu\text{Ci}}{\text{ml}} =$

4.66×10^{3} ml = 5 liters.

Therefore, each sample of 5 gm of thorium nitrate in 20 ml of liquid should be flushed down the sewer with about 5 liters of water.

Note: the specific activity of various isotopes can be found in the Radiological Health Handbook (9).

SUMMARY

1. Some properties of alpha, beta and gamma radiations:

	Charge	Relative Specific Ionization	Approximate Range		
			Air	Soft Tissue	Bone
α	+2	2500	few inches	several μ	few μ
β	-1	100	several ft	few mm	several μ
γ	0	0	indefinite	indefinite	indefinite

2. The ingestion of any type of radioactive material must be avoided at all costs. High specific activity alpha sources are the most dangerous.

3. External radiation exposures can be minimized by controlling:

a) quantity and type of radiation source,

b) length of exposure,

c) distance,

d) shielding.

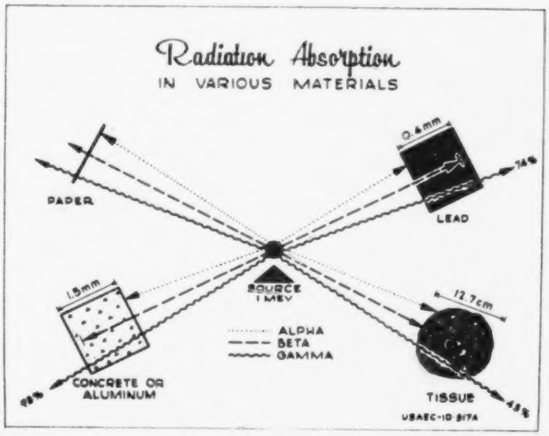


Fig. 6

4. Internal radiation exposures can be controlled by reducing the probability of isotopes entering the body by:

   a) inhalation,
   b) ingestion,
   c) injection,
   d) absorption through the skin.

5. Experiments should be carefully planned and carried out to minimize both accidents and exposure time.

6. Our bodies have no built-in warning system that tells us when we are in a high radiation area. Therefore radiation areas must be clearly marked, the strength of the source known and any hazards clearly understood by both teacher and student.

7. The Atomic Energy Commission places limits on the quantity of radioisotopes most teachers can possess or use at any one time. Because of this limitation, injurious doses of radiation could be received by a high school student in a laboratory situation only as a result of gross carelessness, or through ignorance of the presence of radiation.

8. The guidelines for the use of radioisotopes in the high school classroom are set forth in NCRP Report No. 32. These guidelines were adhered to in this article. Reference should be made to this report if questions arise which this article does not answer.

9. Radioactivity should be respected but not feared. Fear implies a lack of knowledge and understanding of the subject. Good instruction on the part of the teacher will win respect for both himself and the subject.

REFERENCES

1. Glasstone, Samuel, Sourcebook on Atomic Energy, second ed., D. Van Nostrand Company, Inc., Princeton, N.J., 1958.

2. U.S.A.E.C., 18 Questions and Answers About Radiation, Supt. of Documents, U.S. Government Printing Office, Washington 25, D.C.

3. NCRP Report No. 32, Radiation Protection in Educational Institutions, July 1, 1966, NCRP Publications, P.O. Box 4867, Washington, D.C. 20008.

4. ICRP Publication 6, Radiation Protection: Recommendations of the International Commission on Radiological Protection, 1962, published for the International Commission on Radiological Protection by the MacMillan Company, New York (1964).

5. Joseph C. Aub, Robley D. Evans, Louis H. Hempelmann, and Harrison S. Martland: "The Late Effects of Internally Deposited Radioactive Materials in Man," Medicine, 31: 221-329, September 1952.

6. Sommerville, J.L. (Editor), The Isotope Index, published by Scientific Equipment Company, P.O. Box 19086, Indianapolis, Indiana.

7. Code of Federal Regulations (CFR), Title 10, Atomic Energy, Chapter 1, Part 31 (Government Printing Office, Washington, D.C.).

8. Code of Federal Regulations (CFR), Title 10, Atomic Energy, Chapter 1, Part 20 (Government Printing Office, Washington, D.C.).

9. Quimby, Edith H., "Safe Use of Ionizing Radiation In Secondary Schools," The Physics Teacher, 3, 158-160, April, 1965.

10. Division of Radiological Health, ed., Radiological Health Handbook, U.S. Department of Health, Education & Welfare, Washington, D.C., 1960.

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Information on the safe use of radioisotopes in high school situations:

Braestrup, C.B., "Radiation Protection in Teaching Institutions," American Journal of Physics, Vol. 34, No. 12, December 1966.

Cloutier, Roger J., "Radiation Safety," The Science Teacher, Vol. 30, No. 8, December 1963.

Dunavant, B.G., "Radiation Safety in the High School Laboratory," The American Biology Teacher, Vol. 27, No. 6, August 1965.

Miner, T.E., "Radiation Protection in Schools," The Science Teacher, Vol. 33, No. 3, March 1966.

NBS Handbook 92, Safe Handling of Radioactive Materials, U.S. Government Printing Office, Superintendent of Documents, Washington, D.C. 20402.

NCRP Report No. 24, "Protection Against Radiations from Sealed Gamma Sources," 1960, NCRP Publication, P.O. Box 4867, Washington, D.C. 20008.

NCRP Report No. 26, "Medical X-Ray Protection Up To Three Million Volts," 1961, NCRP Publication, P.E. Box 4867, Washington, D.C. 20008

NCRP Report No. 32, Radiation Protection in Educational Institutions, NCRP Publications, P.O. Box 4867, Washington, D.C. 20008.

Quimby, Edith H., "Safe Use of Ionizing Radiation in Secondary Schools," The Physics Teacher, Vol. 3, No. 4, April 1965.

Shaw, Edward I., Radiological Safety, USAEC Report No. TID-18616 (Rev.), April, 1965.

Summary of the Properties of α, β and γ Radiations

Radiation loses energy by interaction with matter in the ways summarized in Table 1. Whereas an α or β particle loses its energy gradually in a series of interactions with many different atoms, the absorption of a gamma-ray photon is a "one shot" affair. This is why γ-ray absorption follows a negative exponential law, but α and β absorption does not.

Table 1: Some Properties of α, β and γ Radiations.

	Charge (e)	Rest Mass (amu)	Relative Specific Ionization of Air	Range in Air	Method of Interacting With Matter	Effective Shielding Materials	Typical Energies (MeV)	Typical Speeds (%c)
α	+2	4	2500	few inches	ionizing collisions	paper, dead skin	4-10	4.7-7.3
β	-1	$\frac{1}{1837}$	100	several ft.	ionizing collisions	lucite, glass, aluminum	0.025-3.5	25-99
γ	0	0	1	indef-inite	1.Photo-electric interact. 2.Compton scattering 3.Pair Pro-duction	lead, concrete	0.04-3.2	100

The energies of α, β and γ radiation may be classified as soft, medium, or hard:

Table 2: Energy Classification

	Energy Classifications (Mev)			
	Soft	Medium	Hard	Spectra
α	The range of α energies is small			Discrete
β	<0.3	0.3 - 1.5 Mev	1.5 - 3.5	Continuous
γ	<0.5	0.5 - 1.0 Mev	>1.0	Discrete

NOTES:

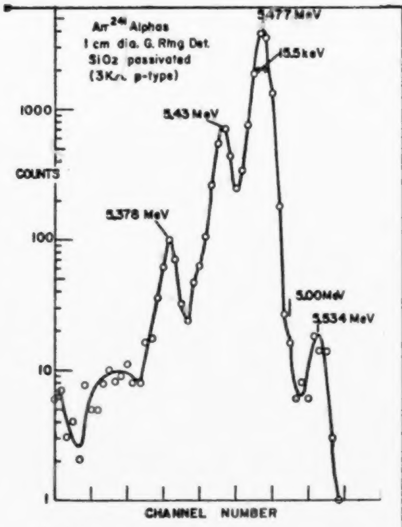
1. Most β's have energies in the vicinity of 1 Mev.
2. γ-rays with energies <0.1 Mev are considered very soft.
3. Radiations travel through matter until all their energy is lost through interactions with the atoms which compose the matter. These interactions are summarized in Table 1.
4. A rapidly accelerated or decelerated charged particle such as a β-particle will radiate X-rays (bremsstrahlung). For this reason, aluminum is a better shield for betas than is lead because of less scattering and less bremsstrahlung production.

Alpha, Beta and Gamma Spectra

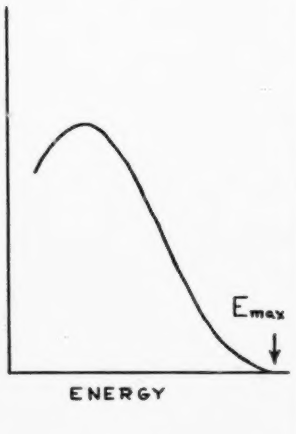
The energy spectrum of α and γ radiation from a given source shows distinct peaks (Table 3, A and C.) These peaks correspond to transitions between discrete nuclear energy levels (just as in the visible region spectral lines correspond to transitions between electronic energy levels).

On the other hand, the energy spectrum of β particles is, typically, continuous. When the energy of β particles emitted by a given isotope is quoted (e.g., Table of Isotopes in Handbook of Chemistry and Physics), it is usually the end-point of maximum energy (E_{max}, Table 3b). The average energy of an emitted particle is about one third of E_{max}. It can be shown that the difference in nuclear energy levels in an isotope undergoing β decay is equal to E_{max}. To maintain the conservation of energy in cases where the β energy is less than E_{max}, Pauli (1930) postulated the existence of a new particle, the neutrino, to carry off the extra energy. The existence of the neutrino was confirmed some 30 years later.

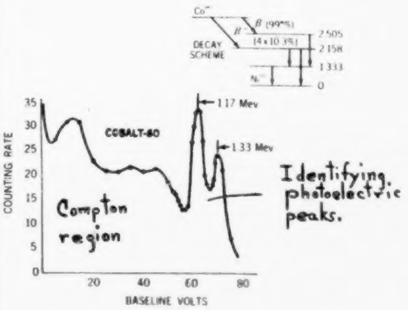
Table 3: Summary of Alpha, Beta and Gamma Spectra



A: ^{241}Am alpha spectra. (Solid state detector)



B: Typical beta spectrum.



C: ^{60}Co gamma spectra (NaI(Tl) crystal coupled to a multi-chan. analyzer)

THE PROVISION FOR AND THE USE OF "GENERALLY LICENSED" RADIOISOTOPES IN THE HIGH SCHOOL CLASSROOM:

The quantity of radioisotopes used in the high school classroom is usually limited to very small amounts that are generally licensed by the Atomic Energy Commission. These are available for purchase from quite a number of suppliers. The complete listing of these (termed "generally licensed" by the AEC, "exempt" by states, and "license free" by some suppliers) is indicated in Table 1. The complete listing is also given in Title 10, Chapter 1, Part 31 of the Code of Federal Regulations (CFR). A teacher may purchase any of these provided that he or she does not at any one time possess or use more than a total of ten such quantities. Although generally licensed quantities may be purchased with-

Table 1. GENERAL LICENSED QUANTITIES

Byproduct material	Column No. 1	Column No. II
	Not as a sealed source (microcuries)	As a sealed source (microcuries)
Antimony (8b 124)	1	10
Arsenic 76 (As 76)	10	10
Arsenic 77 (As 77)	10	10
Barium 140—Lanthanum 140 (Ba-La 140)	1	10
Beryllium (Be 7)	50	50
Cadmium 109—Silver 109 (CdAg 109)	10	10
Calcium 45 (Ca 45)	10	10
Carbon 14 (C14)	50	50
Cerium 144—Praseodymium (CePr 144)	1	10
Cesium-Barium 137 (CsBa 137)	1	10
Chlorine 36 (Cl 36)	1	10
Chromium 51 (Cr 51)	50	50
Cobalt 60 (Co 60)	1	10
Copper 64 (Cu 64)	50	50
Europium 154 (Eu 154)	1	10
Fluorine 18	50	50
Gallium 72 (Ga 72)	10	10
Germanium 71 (Ge 71)	50	50
Gold 198 (Au 198)	10	10
Gold 199 (Au 199)	10	10
Hydrogen 3 (Tritium) (H 3)	250	250
Indium 114 (In 114)	1	10
Iodine 131 (I 131)	10	10
Iridium 192 (Ir 192)	10	10
Iron 55 (Fe 55)	50	50
Iron 59 (Fe 59)	1	10
Lanthanum 140 (La 140)	10	10
Manganese 52 (Mn 52)	1	10
Manganese 56 (Mn 56)	50	50
Molybdenum 99 (Mo 99)	10	10
Nickel 59 (Ni 59)	1	10
Nickel 63 (Ni 63)	1	10
Niobium 95 (Nb 95)	10	10
Palladium 109 (pd 109)	10	10
Palladium 108—Rhodium 108 (Pd-Rh 103)	50	50
Phosphorus 32 (P 32)	10	10
Polonium 210 (Po 210)	0.1	1
Potassium 42 (K-42)	10	10
Praseodymium (Pr 143)	10	10
Promethium 147 (Pm 147)	10	10
Rhenium 186 (Re 186)	10	10
Rhodium 105 (Rh 105)	10	10
Rubidium 86 (Rb 86)	10	10
Ruthenium 106—Rhodium 106 (RuRh 106)	1	10
Samarium 153 (Sm 153)	10	10
Scandium 46 (Sc 46)	1	10
Silver 105 (Ag 105)	1	10
Silver 111 (Ag 111)	10	10
Sodium 22 (Na 22)	10	10
Sodium 24 (Na 24)	10	10
Strontium 89 (Sr 89)	1	10
Strontium 90—Yttrium 90 (SrY)	0.1	1
Sulfur 35 (S 35)	50	50
Tantalum 182 (Ta 182)	10	10
Technetium 96 (Te 96)	1	10
Technetium 99 (Te 99)	1	10
Tellurium 127 (Te 127)	10	10
Tellurium 129 (Te 129)	1	10
Thallium 204 (Tl 204)	50	50
Tin 113 (Sn 113)	10	10
Tungsten 185 (W 185)	10	10
Vanadium 48 (V 48)	1	10
Yttrium 90 (Y 90)	1	10
Yttrium 91 (Y 91)	1	10
Zinc 65 (Zn 65)	10	10
Beta and/or Gamma emitting by-product material not listed above.	1	10

out the need of any specific license from the AEC, the user is *not* exempt from adhering to the regulations that are concerned with their use; hence, it is recommended that teachers obtain copies of Title 10, Part 31 of the CFR.

"Generally licensed" quantities of materials *cannot* be added together to obtain a source of higher activity. If higher activities are desired, proper authorization must be obtained for their acquisition. Hence, if a teacher wants a 30 μCi source of ^{32}P, he cannot buy three 10 μCi liquid sources and pour them all together.

The limitation on quantity by the Atomic Energy Commission *practically* assures the safety of the persons using or coming in contact with radioisotopes in the high school program. However, the fact that they are radioactive materials and can constitute a safety hazard should always be kept in mind and the methods of controlling both external and internal hazards should become a part of both the student's concern as well as the concern of the teacher.

A "generally-licensed" or "exempt" source, when used for a short time such as one of two hours, represents a negligible external hazard. However, if it were to be kept close to the skin for many hours, injurious effects could possibly be produced. Radiation sources should, therefore, not be carried in pockets or handled without proper tools. Adequate precautions should be taken to prevent radioactive materials, *irrespective of amount*, from gaining entry to the body, e.g., through the mouth, the nose, or the skin.

Just about any laboratory exercise involving the use of radioisotopes to be done at the high school level can be accomplished using "generally licensed" quantities will suffice. As a rule-of-thumb in choosing radioisotopes to be used in a classroom experiment, choose the source of minimum strength (activity) required to perform the experiment.

SUPPLIERS OF GENERALLY LICENSED QUANTITIES OF RADIOISOTOPES:

The following is the list of suppliers of generally licensed quantities of radioisotopes that was used in this survey. The list consists of six of the largest suppliers of such radioisotopes in the country. However, the list is not exhaustive nor are these suppliers recommended. Certainly they are not recommended over others which someone else might list.

BA Baird-Atomic, Inc.
33 University Road
Cambridge, Mass. 02138

Cenco Central Scientific Company
1700 Irving Park Road
Chicago, Ill. 60613

M Macalaster Scientific Corporation
186 Third Avenue
Waltham, Mass. 02154

NENC New England Nuclear
575 Albany Street
Boston, Mass. 02118

NC Nuclear-Chicago Corporation
33 East Howard Avenue
Des Plaines, Ill. 60018

TL Tracerlab-Div. of Lab. for Electronics, Inc.
1601 Trapelo Road
Waltham, Mass. 02154

W The Welch Scientific Company
7300 N. Linder Avenue
Skokie, Ill. 60078

A more extensive list can be obtained from the Division of Nuclear Education and Training, United States Atomic Energy Commission, Washington, D.C. 20545. Their most recent list (Dec. 1966) appears on page 7. *The Isotope Index*, put out by the Scientific Equipment Company, P. O. Box 19086, Indianapolis, Indiana 46207 contains probably the most complete listing of all such companies.

SUPPLIERS OF SMALL QUANTITIES OF RADIOISOTOPES

AEC LISTING

Abbott Laboratories
Radio-Pharmaceuticals
P. O. Box 1008
Oak Ridge, Tennessee 37830

Atomic Corporation of America
7901 San Fernando Road
Sun Valley, California 91352

Beta Industries, Inc.
P. O. Box 1407
2275 Ted Dunham Avenue
Baton Rouge, Louisiana 70821

Chem Trac
Radiochemical Division of
Baird Atomic, Inc.
33 University Road
Cambridge, Massachusetts 02138

General Nuclear, Inc.
9320 Tavenor
Houston, Texas 77034

General Radioisotopes Processing Corp.
3000 San Ramon Valley Boulevard
San Ramon, California 94583

Iso-Serve, Inc.
131 Portland Street
Cambridge, Massachusetts 02139

New England Nuclear Corp.
575 Albany Street
Boston, Massachusetts 02111

Nuclear Chicago Corp.
333 East Howard Avenue
Des Plaines, Illinois 60018

Nuclear Consultants Corp.
9842 Manchester Road
St. Louis, Missouri 63119

Nuclear Research Chemicals, Inc.
P.O. Box 6458
100 North Crystal Lake Drive
Orlando, Florida 32803

Nuclear Science & Engineering Corp.
P. O. Box 10901
Pittsburgh, Pennsylvania 15236

Nucleonic Corporation of America
196 Degraw Street
Brooklyn, New York 11231

Schwarz Bio-Research, Inc.
Mountainview Avenue
Orangeburg, New York 10962

Squibb, E. R. and Sons
Radiopharmaceutical Department
Georges Road
New Brunswick, New Jersey 08902

Tracerlab
Technical Products Division
1601 Trapelo Road
Waltham, Massachusetts 02124

U. S. Nuclear Corp.
P. O. Box 208
Burbank, California

Volk Radiochemical Company
8260 Elmwood Avenue
Skokie, Illinois 60076

These companies are catalogued in the Isotope Index, put out by the Scientific Equipment Company, P. O. Box 19086, Indianapolis, Indiana 46207.

The Annual Buyers Guide issue of Nucleonics magazine carries a good list of nuclear equipment and radioisotopes Suppliers.

RADIOACTIVE DISC SOURCES:

Solid radioactive sources may be obtained in the form of a sealed heat-resistant, waterproof plastic disc. An extremely thin Mylar film permits the passage of the desired radiation. These sources provide various types of activity at different energy levels. They are ideal for studies in backscatter, adsorption, isotope identification and for the demonstration of various other properties of radiations. Table 2 is a rather complete listing of low cost generally licensed uncalibrated radioactive disc sources that are available for high school use. For demonstration purposes, the disc sources with a half life greater than one year are recommended for economy reasons. (See Table 2)

Notes: *Alpha emitting Americium-241 and can be purchased from Cenco, but a specific Atomic Energy Commission license is required.

(TL) Sumpolizes a 0.1 μCi disc source sold by Tracerlab for $4.00.

RADIOACTIVE LIQUID SOURCES:

Solutions of radioactive salts are available in generally licensed quantities. Their use includes the demonstration of nuclear phenomena, counting techniques, tracer studies, volume determinations, etc. Table 3 is a rather complete listing of the liquid sources that are available. A glance at the table shows that a wide range of alpha, beta, and gamma radiations of various energies and half lives can be obtained. Because of the internal hazard and the possibility of contamination of lab areas, liquid sources of relatively short half life (months or less) are recommended. Short-lived radioisotopes are generally shipped to arrive at maximum activity. (See Table 3)

Americium-241 and Neptunium-237 solutions may be purchased from Cenco, but their purcahse requires a specific AEC license.

Pipetting of radioactive solutions should never be done by mouth. Indirect methods must always be used. Various inexpensive types of pipettors are available on the market.

Many suppliers of radioisotopes require a minimum order. Ordering requirements should always be checked before orders are mailed in. The prices listed in this survey are merely intended to give an idea of the approximate cost of the various isotopes available. Each supplier reserves the right to change prices at any time. Therefore, prices should always be checked before orders are filled out.

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Table 2: Generally Licensed Uncalibrated Radioactive Disc Sources. (Low Cost.)

Isotope	Half-Life	Activities Available (μCi)	Radiation (Mev)			Suppliers	Range of Prices (dollars)
			Principal Alpha Energies (MeV)	Maximum Beta Energies (MeV)	Principal Gamma Energies (MeV)		
*Americium-241	462y	0.1	5.53,5.48,5.31		Complex	Cenco	6.00
Barium-133	10.7y	10			.357	BA, Cenco,(TL)	8-15
Bismuth-210	22y	0.01-0.05		1.17		BA, TL	10-15
Cadmium-109	470d	1-10			0.087	BA,Cenco,(TL)	8-15
Calcium-45	165d	10		.25		Cenco	6.00
Carbon-14	5560y	0.1-50		.155		BA,Cenco,NENC,NC,TL	5-10
Cerium-144/				0.32	weak		
Praseodymium-144	285d	10		2.97	Complex	Cenco, (TL)	6.00
Cesium-134	2.2y	9		0.66	Complex	NC	5.00
Cesium-137	30y	0.1-10		.52	.66	BA,Cenco,NC,TL	5-10
Chlorine-36	3.0×10^5y	0.02		0.714		BA,NENC,TL	10-15
Cobalt-57	270d	1.0		β^+	0.123	BA	15.00
Cobalt-60	5.26y	0.02-10		.31	1.17,1.33	BA,Cenco,NENC,TL,W	5-10
Lead-210/							
Bismuth-210	22y	0.02-10	5.06	1.17		BA,Cenco,NC,(TL)	6-10
Manganese-54	310d	1-10			.840	BA,Cenco,(TL)	10-15
*Neptunium-237	20×10^6y	0.1	4.79,4.52,4.87		Complex	Cenco	6.00
Polonium-210	138d	0.1-1.0	5.3			BA,Cenco,W	5-10
Promethium-147	2.6y	0.1-10		.223		BA,Cenco	6-15
Protactinium-234	4.5×10^9y	0.01		2.31		BA	15.00
Radium	1600y	15 μgm				BA,NC	≈10.00
Ruthenium-106/				.04	✓		
Rhodium-106	371d	10 μCi		3.5	Complex	Cenco,(TL)	6.00
Sodium-22	2.6y	0.02-10		β^+, 0.54	1.27	BA,Cenco,(TL)	15-20
Strontium-90	28y	0.05-1.0		.61;2.24		BA,Cenco,NC,TL	5-10
Sulfur-35	89d	50		.167		Cenco, (TL)	6.00
Technetium-99	2×10^5y	0.02-0.05		.290		BA,NENC	10-15
Thalium-204	3.6y	0.02-50		.77		BA, Cenco, M, NC, W, (TL)	5-15
Uranium	4.5×10^9y	≈ 2000 α dpm	✓	✓	✓	BA,Cenco,NC,(TL)	6-10
Zinc-65	246d	10		β^+, 33	1.11	Cenco, (TL)	6.00

Notes: *Alpha-emitting Americium-241 and Neptunium-237 disc sources can be purchased from Cenco, but a specific Atomic Energy Commission license is required.

(TL) Symbolizes a 0.1 μCi disc source sold by Tracerlab for $4.00.

ALL-PURPOSE RADIOACTIVE SOURCES:

TABLE 4. GOOD ALL-PURPOSE RADIOACTIVE SOURCES

α	β	γ	Short-Lived Liquid Sources
Ra	^{90}Sr	^{60}Co	^{131}I, ^{32}P
RaDEF	^{204}Tl	^{137}Cs	^{45}Ca, ^{35}S

Notes: 1. Radium is a good cloud chamber source. However, it must be remembered that radium sources contain more than just radium. Since all of the daughter products of radium are present in the source in equilibrium amounts (after a period of time) and since several of these daughter products are also alpha emitters, a radium tip will emit several different alphas with energies which range from 4.5-10 MeV. In the cloud chamber, alpha tracks of varying lengths will be observed.

If the radium source is very thin, some of the tracks can be associated with their parent atoms by matching the observed ranges in air (alcohol vapor) with their approx-

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Table 3. Uncalibrated Radioactive Liquid Sources

Isotope	Half-Life	Activities Available (μCi)	Maximum Beta Energies (MeV)	Principal Gamma Energies (MeV)	Chemical Form	Suppliers	Ave. Cost (dollars)	Volume (ml.)
Barium-133	7.2y	1		0.358	$BaCl_2$	NC,TL BA,Cenco NENC,	6-8	5
Cadmium-109	470d	10		0.087,EC	$Cd(NO_3)_2$	Cenco,NC	7.5-8	5
Calcium-45	165d	10	0.254		$CaCl_2$	BA,Cenco, NC, W	6-8	5
Carbon-14	5560y	5-50	0.155		Na_2CO_3	BA,Cenco, NC, TL	6-15	5
Carbon-14	5560y	5	0.155		C_6H_5COONa	NENC, M	7	5
Carbon-14	5560y	50	0.155		CH_3COON_a	NC	16	20-40 mCi/mM
Carbon-14	5560y	50	0.155		$(CH_3CO)_2O$	NC	17	5-30 mCi/mM
Carbon-14	5560y	50	0.155		NH_2CH_2COOH	NC	16	5-25 mCi/mM
Cerium-144/ Praseodymium-144	285d	1	0.32 2.98	some	$CeCl_3$	Cenco,NC, W, M,	6-7.5	5
Cesium-137/ Barium-137	30y	1	0.51	0.66	C_5Cl	TL BA,Cenco, NENC,NC	6-7.5	5
Chlorine-36	3.0×10^5y	1	0.71	EC,no γ	HCl	BA	6	5
Cobalt-57	270d	1	β+	EC,γ	C_0Cl_2	BA,NENC,TL NC, TL, W	6-7.5	5
Cobalt-60	5.26y	1	0.310	1.17,1.33	C_0Cl_2	BA, Cenco, NENC, M	6-7.5	5
Iodine-131	8.04d	10	0.33,0.61	0.36, 0.64	NaI	BA,NC,W,M	7.5-12	5-10
Iron-55	2.7y	5-10		EC,^{1}no γ	$FeCl_3$	BA,NENC, TL, M	6-7	5
Lead-210/ Bismuth-210	22y	1-10	0.017 1.17^2	0.047	$Pb(NO_3)_2$	TL, W BA,Cenco, NENC,NC,M	6-7.5	5
Manganese-54	314d	1		0.84,EC	$MnCl_2$	BA,Cenco, NENC, TL	6-10	5
Mercury-203	47d	1	0.210	0.279	$Hg\ (NO_3)_2$	NC	7.5	5
Nickel-63	125y	1 μCi	0.067		$NiCl_2$	BA,NENC, TL	6-7	5
Phosphorus-32	14.2d	10	1.71		Na_3PO_4 or H_3PO_4	BA,NENC, NC,W,M	6-12	5
Promethium-147	2.6y	5-10	0.22		$PmCl_3$	BA,Cenco, NENC, TL	6-7	5
Ruthenium-106/ Rhodium-106	371d	1	0.039 3.55	Complex	$RuCl_3$	Cenco, NC, TL	6	?
Sodium-22	2.6y	1-10	β^+, 0.54	1.28,EC	NaCl	BA,Cenco, NENC,M	6-20	5
Sulfur-35	87.2d	50	0.167		S in ϕ	Cenco	6	?
Sulfur-35	87.2d	50	0.167		S in ϕCH_3	NC	7.5	2
Sulfur-35	87.2d	5-50	0.167		H_2SO_4	BA,NENC, NC, TL	6-8	1-5
Strontium-90/ Yttrium-90	28y	0.1	0.54 2.26		$SrCl_2$	NC, TL BA,Cenco, NENC,NC, TL, M	6-7.5	5
Thallium-204	3.6y	1-50	0.77	EC,no γ	$TlNO_3$	BA,Cenco, NENC,	6-7.5	5
Uranyl Nitrate (solid)	4.5×10^9y	2-5 grams	✓	✓	$UO_2(NO_3)_2 \cdot 6H_2O$	BA,Cenco, NENC,TL NC,TL,W	6-10	
Zinc-65	245d	5-10	β^+, 0.325	1.11,EC	$ZnCl_2$	BA,Cenco, NENC,	6-7.5	5

Notes: 1. Iron-55 emits characteristic Mn x ray of 5.9 KeV.
2. Bismuth-210 also emits 5.03 MeV alphas.
3. Americium-241 and Neptunium-237 solutions may be purchased from Cenco, but their purchase requires a specific AEC license.

imate energy as obtained on a range vs. energy graph. The energy obtained can then be matched with the known energies of the alphas emitted by radium and its daughters. If the radium source is thick, this parent identification cannot be done accurately because many of the alphas will lose energy within the source before they emerge into the volume of the chamber and hence their range will be shortened. The net result is that a fairly continuous spectrum of alpha energies is observed.

2. Cenco markets on Alpha Ray Tip (Radium) for $10.50. Welch markets an Alpha Ray Source (Radium) for $1.25.
3. Unlike radium sources which emit alphas with energies ranging from 4.5 - 10 MeV, Radium DEF sources are monoenergetic. A radium DEF source consists of radium E and F in secular equilibrium with Radium D.

$$\mathrm{RaD}\quad \overset{\beta}{22\mathrm{y}}\quad \mathrm{RaE}\quad \overset{\beta}{5.0\mathrm{d}}\quad \mathrm{RaF}\quad \overset{\alpha}{138\mathrm{d}}\quad \text{stable lead}$$

$(^{210}\mathrm{Pb})$ $(^{210}\mathrm{Bi})$ $(^{210}\mathrm{Po})$ $(^{206}\mathrm{Pb})$

Since Radium D and E are essentially beta emitters, only the 5.3 MeV alphas of Radium F are observed in the cloud chamber. Hence, Radium DEF is a good source for showing that alphas are monoenergetic (which implies an alpha spectrum is discrete). The reason RaDEF cloud chamber sources are manufactured instead of pure RaF sources is because the half life of RaF is only 138 days. The half life of RaD is 22 years, and the half lives of all of its radioactive daughters (RaE and RaF) are all much less than 22 years. All of the daughters must therefore decay at the same rate as RaD. This means that the RaDEF source has an effective half life of 22 years.

In summary:

RaDEF is a good monoenergetic alpha source.

Radium is a good source for demonstrating the presence of the radioactive daughter products which exist in secular equilibrium with radium.

4. Macalaster Scientific Corporation (186 Third Avenue, Waltham, Mass. 02154) markets a RaDEF cloud chamber source for $1.50.
5. Both Strontium-90 and Thallium-204 are considered pure beta emitters.
6. Both Cobalt-60 and Cesium-137 give off beta particles as well as gamma radiation. However, the beta particles can easily be shielded out with aluminum foil, lucite, plastic or glass.

Use of the Electroscope as a Measuring Instrument in Radioactivity

If some of your students are interested in a side project on the use of the electroscope as a measuring instrument in radioactivity, you can start them off by suggesting that they actually measure the capacity of one of your laboratory electroscopes. For this, the related physical quantities are:

$$C = \frac{\varepsilon_0 A}{d},$$

where:

C = capacity in farads;

A = area of one of parallel plates in m^2;

d = distance between the plates in m;

ε_0 = the electrical constant;
8.9×10^{-12} $\text{coul}^2/\text{nt}\cdot\text{m}^2$.

Of course, the electroscope is not a parallel plate capacitor—only a rough approximation to one—but don't tell this to the students at first; it makes an excellent question about the nature of experimental accuracy later on.

The capacitor carries a charge: $Q = CV$. If you consider that the plate area is about 0.0005 m^2, and that $d = 0.05$ m, the capacity $C = 8.9 \times 10^{-14}$ farads—this can be simplified to 10^{-13} farads without causing complications. Then, the charge on the fully charged electroscope = $10^{-14} \times 10^4 = 10^{-9}$ coul.

If you have some uranium salt available, this experiment can be extended. Ten mg of U will emit about 120 alpha particles/sec, with an energy of 4.2 MeV/particle. But only 35 eV of energy are required to produce one ion pair in air. So, if the alpha rays are directed into the electroscope, the air inside will ionize to the following extent:

$$\frac{4.2 \times 10^6 \times 120}{35}$$

$$= 1.44 \times 10^7 \text{ ion pairs/sec.}$$

If the leaves of the electroscope are charged negatively, the positive ions created in the air will move to the leaves at the above rate.

$$1.44 \times 10^7 \text{ ions/sec}$$

$$\times\ 1.6 \times 10^{-19} \text{ coul/ion}$$

$$= 2.3 \times 10^{-12} \text{ coul/sec.}$$

From the above, it would take $+10^{-9}$ coul to neutralize the negatively charged leaf, the total time to collapse the leaves should be

$$\frac{10^{-9}}{2.3 \times 10^{-12}} \text{ sec} = 440 \text{ sec},$$

or about 7 minutes. Ask the students who want to try this to think about what might cause deviations from the exact time predicted.

Radiation Detecting Devices

Detector	Types of Radiation Measured	Typical Full Scale Readings	Use	Minimum Energy Measured	Directional Dependence	Advantages	Possible Disadvantages
Geiger-Müller counter	Beta, x, gamma	0.2 to 20 mR/hr or 800 to 80,000 cpm	Survey	20 keV for x rays. 150 keV for betas.	Low for x or gamma	Rapid response	1. Strong energy dependence. 2. Possible paralysis of response at high count rates or exposure rates. 3. May be affected by uv light.
Ionization chamber	Beta, x, gamma	3 mR/hr to 500 R/hr	Survey	20 keV for x rays. Variable for betas.	Low for x or gamma	Low energy dependence	1. Relatively low sensitivity. 2. May be slow to respond.
Pocket ionization chamber & dosimeter	x, gamma	200 mR to 200 R	Survey & Monitoring	50 keV	Low	1. Relatively inexpensive. 2. Gives estimate of integrated dose. 3. Small size.	Subject to accidental discharge.
Film	Beta, x, gamma, neutrons	10 mR and up	Survey & Monitoring	20 keV for x rays. 200 keV for betas.	Moderate	1. Inexpensive. 2. Gives estimate of integrated dose. 3. Provides permanent record.	1. False readings produced by heat, certain vapors and pressure. 2. Great variations with film type and batch. 3. Strong energy dependence for low energy x rays.

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"Atomic Fuel"
"Atomic Power Safety"
"Atoms in Agriculture"
"Controlled Nuclear Fusion"
"Direct Conversion of Energy"
"Fallout from Nuclear Tests"
"Food Preservation"
"Lab Experiments with Radioisotopes"
"Microstructure of Matter"
"Neutron Activation Analysis"
"Nuclear Power and Merchant Shipping"
"Nuclear Reactors"
"Our Atomic World"
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"Power from Radioisotopes"
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Suggested Answers to Unit 6 Tests

Test A

ITEM	ANSWER	SECTION OF UNIT
1	B	21.6
2	C	21.6
3	B	21.6
4	D	21.4
5	D	21.1
6	A	21.3, 21.4
7	D	23.7
8	B	24.8
9	E	22.1, 22.2
10	A	22.1, 22.2
11	D	22.6
12	D	21.3, 21.4
13	C	24.2
14	B	23.5
15	C	24.5, 24.6

Answers
Test A

Group I

1. Section of Unit: 24.4

Given: atomic mass of H^1 = 1.0080 amu
atomic mass of L^7 = 7.0160 amu
atomic mass of He^4= 4.0026 amu
1 amu = 931 MeV

$${}_1H^1 \quad + \quad {}_3Li^7 \longrightarrow {}_2He^4 \quad + \quad {}_2He^4$$

$$1.0080 + 7.0160 \longrightarrow 2(4.0026)$$

$$8.0240 \longrightarrow 8.0052$$

$$\Delta m = 0.0188 \text{ amu}$$

$$(0.0188 \text{ amu})(931 \text{ MeV/amu}) = 17.5 \text{ MeV}$$

2. Sections of Unit: 22.1, 22.2

$${}_{92}M^{238} \xrightarrow{\alpha} {}_{90}Th^{234} \xrightarrow{\beta} {}_{91}Pa^{234} \xrightarrow{\beta} {}_{92}M^{234}$$

3. Section of Unit: 21.8

"The law of disintegration of a radioactive substance is a statistical law" because:

i) it applies to a large population.
ii) it makes no prediction regarding an individual atom.
iii) it does not attempt to explain cause.

4. Section of Unit: 21.8

$$8 \text{ mg} \longrightarrow 4 \text{ mg} \longrightarrow 2 \text{ mg} \longrightarrow 1 \text{ mg}$$

This reduction will take 3 half-lives = 3(3.05) min
= 9.15 min.

5. Sections of Unit: 24.5-24.8

The list of topics suitable for discussion within the framework of this question is long. The following examples are by no means intended to exhaust all the possibilities. A sufficient answer could involve a brief discussion of the effects of using atomic energy in electric power production, transportation, or water desalination. In addition, a student may wish to consider the effects of military applications, or the consequences of fallout.

Answers
Test A

Group II

1. Sections of Unit: 24.6, 24.7

   a) The function of the moderator in a nuclear reactor: fission is caused by the 'capture' of a neutron by a heavy nucleus. There is a greater probability of this occurring if the fissionable material is bombarded with slow neutrons. Fast neutrons lose energy and are slowed through collisions as they pass through a moderator.

   b) Heavy water is an effective moderator since the mass of the atoms it contains is approximately equal to the mass of a neutron. Consequently, a neutron will lose a large fraction of its energy in a collision with an H nucleus. In addition, the density of H atoms in heavy water is high. Neutrons passing through heavy water are not absorbed by the nuclei and are thus available to produce fission. Other moderators, for example, ordinary water, are less effective because they absorb neutrons.

2. Section of Unit: 24.11

   a) The nucleus is regarded as analogous to a charged drop of liquid.

Particles in the nucleus, like the molecules in a liquid drop, are in continual random motion.

As in the evaporation of molecules from the surface of a liquid drop, nuclear particles may gain sufficient energy through chance collisions with other nucleons to overcome the attractive nuclear forces and escape from the nucleus.

   b) i) describes nuclear reactions
      ii) accounts for fission

3. Section of Unit: general

The elbow-shaped object is an electromagnet. Its function is to bend the particle beam, and in doing this to separate out the particles of interest. In addition, the magnet might be used to focus and aim the particle beam.

Suggested Answers to Unit 6 Tests

Test B

ITEM	ANSWER	SECTION OF UNIT
1	C	24.13
2	D	21.3, 21.4
3	E	21.3, 21.4
4	A	Study Guide p. 85 & Unit V
5	A	21.8
6	C	23.7
7	B	21.2
8	D	23.4
9	B	22.1, 22.2
10	E	21.5
11	C	24.5, 24.6
12	B	24.8
13	A	24.5, 24.6
14	A	21.3
15	C	24.5, 24.6

Answers
Test B

Group I

1. Section of Unit: 21.5

No. The decay constant is the fraction of decaying atoms per unit time. This quantity is observed to be constant for a particular element. Consequently, the decay activity is a function of the number of surviving atoms of the element and must decrease as the number of survivors decreases. Thus, the "total lifetime" of a sample is indefinitely long, for the fewer atoms that are left unchanged in the sample, the fewer will disintegrate per unit time.

2. Section of Unit: 23.8

No. Granted, gold has been produced from other materials. However, these transformations vary greatly, in method and in purpose, from the attempts of the alchemists.

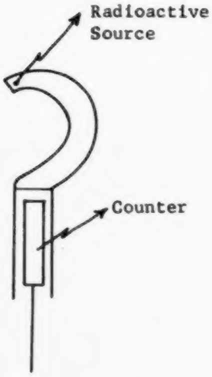
3. Section of Unit: 24.2

The Ba^{141} nuclide is more stable than Ra^{222} nuclide.

4. Section of Unit: 22.1

Nuclides of lead 206 and 214 have the same number of protons but different numbers of neutrons. Thus, they have the same chemical properties but have different atomic masses. In addition, they have different radioactive behavior.

5. Section of Unit: General



The probe that the man is holding includes both a radioactive source and a counter tube. With this he is able to measure the thickness of the pipe walls. However, since the details of the probe are not shown, a satisfactory answer might suggest that a tracer had been introduced earlier and the man was measuring the rate of flow, density, pressure, etc., of the fluid in the pipe.

Group II

1. Sections of Unit: 24.5-24.8

Fission: A heavy nucleus is split into two nuclei of intermediate mass number.

The sum of the binding energies of the two product nuclei is greater than the binding energy of the heavy nucleus. Consequently, energy is released.

Fusion: Two or more nuclei with low mass numbers are joined together to form a more massive nucleus.

The heavy nucleus has more binding energy than the nuclei from which it is formed. Consequently, energy is released.

Both processes can be made to occur on a large scale, and very rapidly, resulting in nuclear explosions. The speed of the fission process can be controlled, resulting in the production of energy at a desired rate. Scientists are now trying to control the rate of the fusion process.

2. Section of Unit: 21.6

When a radioactive atom emits an α or β particle it really breaks into two parts—the α or β particle and a heavy left-over part that is physically and chemically different from the original atom.

3. Sections of Unit: 24.6, 24.7

Nuclear explosions release large amounts of radioactive materials. Winds carry these materials long distances and precipitation brings them down to earth. Some of the radioactivities are long-lived, and are absorbed in growing foodstuffs and eaten by animals and people. Under certain conditions these radioactive materials can cause harmful genetic and somatic effects. For example, one of the long-lived products of a nuclear explosion is strontium 90. This isotope of strontium is similar to calcium 40 in its chemical properties and hence when taken into the body it finds its way into bone material. If present in large quantities its radioactive decay can cause leukemia, bone tumors and other forms of damage.

Suggested Answers to Unit 6 Tests

Test C

ITEM	ANSWER	SECTION OF UNIT	ITEM	ANSWER	SECTION OF UNIT
1	B	21.6	21	D	23.-
2	B	21.6	22	D	23.-
3	C	21.6	23	D	21.3, 21.4
4	B	21.3, 21.4	24	D	general
5	D	21.8	25	B	24.5
6	D	22.-	26	E	23.3
7	D	21.3, 21.4	27	A	24.2
8	E	21.8	28	C	24.5
9	C	21.3, 21.4	29	B	24.8
10	A	21.3, 21.4	30	A	24.8
11	C	21.8	31	C	21.3, 21.4
12	B	21.8	32	C	21.8
13	E	22.5	33	B	21.8
14	A	22.7	34	E	22.1, 22.2
15	A	22.1, 22.2	35	C	21.-
16	E	22.-	36	C	24.8
17	C	23.7	37	B	24.6
18	E	23.8	38	D	24.6
19	A	22.-	39	C	24.6
20	E	23.-	40	A	21.8

Suggested Answers to Unit 6 Tests

Test D

Group I

1. Section of Unit: 23.-

a) ${}_{8}O^{16} + {}_{0}n^{1} \longrightarrow {}_{8}O^{17}$

b) ${}_{8}O^{16}$ and ${}_{8}O^{17}$ are both isotopes of oxygen.

2. Section of Unit: 24.2

Given: mass of ${}_{2}He^{4}$ atom = 4.002403 amu
mass of e^- = 0.000549 amu
mass of p = 1.007276 amu
mass of n = 1.008665 amu
1 amu = 931 MeV

An ${}_{2}He^{4}$ atom consists of 2 electrons, 2 protons and 2 neutrons.

$$\begin{array}{lcr} 2\ p = 2(1.007276) & = & 2.014552 \\ 2\ n = 2(1.008665) & = & 2.017330 \\ 2\ e^- = 2(0.000549) & = & \underline{0.001098} \\ & & 4.032980 \\ {}_{2}He^{4} & = & -\underline{4.002603} \\ \Delta m & = & 0.030377\ \text{amu} \end{array}$$

$$(0.030377\ \text{amu})(931\ \text{MeV/amu}) = 28.28\ \text{MeV}$$

3. Section of Unit: 21.6

A radioactive atom undergoes change on emitting an α or β particle. The original atom is transmuted to one with new physical and chemical properties. Traditionally atoms were considered indestructable and unchangeable.

4. Section of Unit: 21.1

In his studies of uranium Becquerel found that:

a) whether or not the uranium compound was being excited it continued to emit radiations that could penetrate substances opaque to light.

b) the amount of exposure of a photographic plate due to the radiations from the uranium compound was only a function of the amount of uranium present.

5. Section of Unit: 24.13

   a) The physical and chemical effects of various kinds of radiations on biological materials are being studied.
   b) The metabolism of plants and animals is being studied with the aid of minute amounts of radioactive nuclides called isotopic tracers.
   c) Agricultural experiments with fertilizers containing radioactive isotopes have shown at what point in the growth of a plant the fertilizer is essential.
   d) Radioactive isotopes help to determine the details of chemical reactions and of the structure of complex molecules, such as proteins, vitamins and enzymes.
   e) Tracers help to determine rate of flow of blood through the heart and to the limbs, thus aiding in the diagnosis of abnormal conditions.
   f) Certain radioisotopes have been used in the treatment of cancer, blood diseases, brain tumors, and in the diagnosis of thyroid, liver, and kidney ailments.

Group II

1. Section of Unit: 21.8

   1. The fraction of the total number of atoms in a sample which decays per unit time is constant for any type of radioactive atom. Therefore, radioactivity must decrease in proportion to the number of surviving atoms. Thus, the "total lifetime" of a sample is indefinitely long for the fewer atoms that are left unchanged in a sample, the fewer will disintegrate per unit time. Consequently, "total lifetime" is not a useful measure of decay rate.

2. Sections of Unit: 22.1, 22.2

   a) An α-particle emission reduces the positive charge of the nucleus by two units. Consequently, the resulting nuclide holds two fewer electrons in its outer shells. This new nuclide acts chemically like an atom with an atomic number two units less than that of the atom before the α emission occurred.

   b) A β-particle emission increases the positive charge of the nucleus by one unit. Consequently, the resulting nuclide holds one more electron in its outer shells. This new nuclide acts chemically like an atom with an atomic number one unit greater than that of the atom before the β emission occurred.

3. Section of Unit: 24.12

The nuclear shell model assumes that protons arrange themselves in shells and that neutrons can, independently, do likewise. In nuclei with even numbers of neutrons and protons, the more stable nuclei, these shells are filled. This model has been worked out in great detail on the basis of quantum mechanics and is analogous in many ways to the quantum mechanical model of the atom.

The nuclear shell model has successfully correlated the properties of nuclides that emit α or β particles and photons. Furthermore, it has been useful in describing the electric and magnetic fields that surround nuclei.

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